Investigation of Rail Welded Joint Stresses, by using a Narrow Gap Welding Method, in Ballasted Railway Tracks

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Abstract: In the modern railway superstructure construction and maintenance, particularly where higher speeds are required, the rail sections may be welded together to form Continuous Welded Rail (CWR). There are various methods for welding the rails, such as thermite welding, flash-butt welding, gas-pressure welding, enclosed-arc welding, etc. Narrow Gap Welding is another way of welding the rail joints and because of the lower implementation costs, easier, quicker process and acceptable performance, it is usually used over other methods in maintenance operations. Since this method is newer than others, there is lack of knowledge concerning the standard process of narrow gap welding and the factors that affect the final quality. In the narrow gap welding, two different welding electrodes are used for the welding process. One electrode, with higher stiffness, is used for the rail head and the other electrode, with lower stiffness, is used for the rail web and foot. In this research, the relationship between these different welding electrodes and the amount of stress in rail joint was investigated via experiments and modeling, by a finite element method. The results indicate that the number of stresses, in the junction of rail head and web, was reduced by 37%, when the electrode with higher stiffness was used for the whole rail head, plus 1 cm of rail web. Field investigations demonstrated that the performance of rail welds was acceptable.

Keywords: railway superstructure; rail joint; welding electrodes; narrow gap welding; finite element method

1 Introduction

In railway tracks, the use of fishplates and bolts was common to connect the rail sections, before the advent of producing longer rail sections and using welding technology, for the connection of rails in joints [1]. In this method, the rail sections are connected only through the rail web using bolts, nuts and fishplates on both sides of the rail web [2] [3]. This system has numerous disadvantages, such as:

- Creating very large dynamic forces in rail joints when the train passes through the track
- Weakening the railway structure
- Reducing the service life of the track elements including rails, sleepers and the fastening system
- Increasing the cost of maintenance and repair operations by 25%
- Increasing the cost of the maintenance and repair operations for the railway track and rolling stock
- Defects, such as crushing of the end of the rails in joints and failures due to the inherent fatigue
- Generation of excessive noise while the vehicle is passing on the track
- Deterioration of the desired track geometry in a short time [2, 4, 5]

As the speed and the axel loads of the rolling stock increase, the destructive effects of the expansion joints become more important [6] [7]. In order to reduce the negative effects of the expansion joints in railway tracks, there are two solutions: 1-using longer rails and thus reducing the number of expansion joints required to connect rail sections to each other and 2-using the welding techniques to connect the rails to each other (In this way, the expansion joints are completely welded to form CWR tracks) [8-11]. Therefore, welding the rails in joints is done to achieve these goals: increasing the continuous length of the rail and thus reducing the number of joints, fishplates and bolts; overcoming the weakness of the track due to the expansion joints; saving money by reducing the volume of repair and maintenance operations; increasing the service life of the track; and so on [12] [13]. There are different methods of welding the rails in joints in Iranian railways including thermite welding, electric welding, gas pressure welding, electric arc welding and narrow gap welding. Thermite welding is a set of processes in which the filler material is made of molten metal created by a highly exothermic chemical reaction [14-16]. The chemical reaction or thermite usually takes place between the oxide of a metal (iron or copper) and aluminum powder at a high temperature. A rapidly ignited powder is used as a detonator to provide the heat needed to start the reaction [1]. Two examples of the chemical reactions in this type of welding are as given in the following Eq. (1) and (2):

$$Fe_2O_3 + 2Al \rightarrow 2Fe + Al_2O_3 + Heat \quad (1)$$

$$3CuO + 2Al \rightarrow 3Cu + Al_2O_3 + Heat \quad (2)$$

This type of welding is more like casting and there is a mold around the two components that must be welded together [15]. The molten metal produced by this chemical reaction is directed to this mold and is hardened inside the welding mold due to cooling [12]. In this welding method, there is no need for energy supply systems such as electricity generators and the welding process can be carried out anywhere [12]. The main disadvantages of this method are:

1) The welding process generates gaseous pollutants (hydrogen) and also slag.
2) Sometimes the high temperature of the process causes distortion and relatively large deformations at the welding joint [17-19].

Electric welding along with thermite welding is a common method to remove rail joints by welding the rail sections. One of the advantages of electric welding compared to thermite welding is performing the welding process without adding extra material, which has a great impact on the strength of the rail and its service life [13]. Electric welding is done in two different methods in railways. In the first method, the rail sections are welded to the required lengths and then a crane is used to transport them to the site for installation. In the second method, welding operations are carried out by modern fixed and mobile welding machines [20].

Gas pressure welding is another method to build a CWR track. Special equipment is needed to weld the rails in this method and the welding process take more time than the previous methods. This method also requires trained technicians and the welding quality is higher [13].

Narrow gap welding is a relatively newer method than other rail welding methods. In the narrow gap welding method, according to the results of research from 1975 to 2000, the quality of rail at welded joints has improved compared to the original metal [13] [21]. The quality of this type of welding is greatly improved by using the appropriate electrode, designing and optimizing suitable alloys, and using water or air cooling shoes to control the rate of temperature during the welding process. The quality of the narrow gap welding is directly related to the skill and experience of the welding technicians and the welders [13] [21]. Besides, it is very important to provide precise instructions for the whole process which have to be observed, since the slightest change in the correct narrow gap welding process will cause a defect in the welded joint. This factor prolongs the time needed to carry out the narrow gap welding process compared to other rail welding methods, and also causes human errors [8, 13, 22]. Although the narrow gap welding method is currently used in the most railways under construction and has been accepted as a welding method, so far there are no comprehensive and complete instructions for the implementation of this method. In this research, while the existing criteria for narrow gap welding are investigated, the optimal pattern of the electrodes is defined by a finite element method.

2 Narrow Gap Welding

Within the railway industry, the narrow gap welding method is utilized for the construction of CWR tracks and also, for repair and maintenance operations. This method is widely used due to its advantages than other methods of welding namely, lower costs compared to other welding methods and also fulfilling the structural standards needed for railway operations based on the loading and velocity of the rolling stock [23]. As mentioned before, this method requires skilled welding teams, precise welding process and strict regulations and instructions [8, 13, 21, 22].

There are some materials used to perform narrow gap welding including electrodes and retaining molds. The electrodes used in this method must be selected such that they can accommodate to the original rail properties [1]. The elasticity as well as the abrasion resistance of the weld must be proportional to the reference metal and this is possible by selecting the appropriate electrode. Tensile strength parameter should be considered in selecting the appropriate electrode for the rail web and foot, and abrasion resistance along with tensile strength should be considered in selecting the appropriate electrode for the rail head. Welding of rail joints by narrow gap method is done inside a chamber including rails and retaining molds [13]. These molds are made of cast copper whose dimensional characteristics are proportional to the type of electrode, type of rail and operating temperature. The retaining molds must be thermally conductive; therefore, the molds are made of copper. In addition, the molds control the tension of the rail and welding. The molds have several separate sections for the rail web and foot. The retaining molds must be carefully maintained, as they can lose their original geometry, over time [4, 8, 13, 22, 24].

The narrow gap welding method has two steps. The first step is preparation, which its purpose is to prepare the rails and joints for welding. This step must be done carefully and it has to be controlled multiple times. Prior to welding, the rails at the joint must be free of defects like cracks and crushed heads, and if these defects are already occurred, the rails must be ground and cut with the related machines [22]. In the tracks with Vossloh-fastening system, to carry out the welding, only the screws of the near sleepers can be opened. Because when the screws are opened, the dust is infiltrated into the dowels. In order to perform a clean weld, the cross section of the rail at the joint must be completely polished and free of any greasy or impure materials. In this regard, the rail and weld materials are completely connected by using a continuous electric arc between the rail and the electrode, and consequently a perfect weld is created [13]. One of the most important factors in performing a desirable weld by narrow gap method is adjusting the rail joint. The rail ends at the joint should be aligned vertically and horizontally so that the foot, web and head of both rails are in the same direction [8, 21, 25].

The second step is welding the rails. After adjusting the rail joint, the rails at both sides of the joint, are heated to a distance of 100 mm, which is called, preheating [1, 12, 13]. When the rail reaches a certain temperature, the welding process begins. The special mold for the rail foot is fixed at the certain position, before starting the welding process. Then the lowest part of the rail is welded. As mentioned before, accuracy and skill in performing welding are very important in its quality. The electrode used in this step is exerted for both the foot and web [25]. In this research, the mechanical properties of ESAB OK 74.78 electrode are considered for the web and foot. Welding of rail foot is carried on until the beginning of rail web section. At this stage, the special web mold is installed in the desired position and welding process continues. When the web section welding is completed, the head of the joint is welded immediately and without interruption [22]. As previously described, the electrode used in the head of the joint has different materials than the foot and web section. This electrode must have abrasion resistance [25]. In this research, the mechanical specifications of ESAB OK 83.28 electrode have been considered for the head. Following the end of the welding process, the molds are separated and the original rail and the welded joint are leveled using the grinding machine. The last step in narrow gap welding is the post-heating operation [21] [22]. In the post-heating operation, the parts are heated to a certain temperature after welding and then cooled at a gentle rate. This prevents unwanted compressive and tensile stresses from welding process [25].

As illustrated earlier, two different electrodes are used for welding the rail sections in the narrow gap welding method. The electrode used for welding the rail head must resist against abrasion. The properties of the electrodes used in this research are demonstrated in Table 1.

Table 1
The properties of the electrodes in the narrow gap welding

Category	Yield Stress (MPa)
ESAB OK 74.78	600
ESAB OK 83.28	650

One of the most important steps in the narrow gap welding is determining the position where the different electrode must be used for welding the rail head. According to Fig. 1 there are three options for this position. Determining this position will affect the construction, maintenance and repair costs of the railway tracks, since the electrode used for the rail head is more expensive. Also, each of the three patterns “a”, “b” or “c” is effective in finding the stresses created in the weld section. Although experiential observations demonstrate that the best pattern is option “b”, but there are less scientific investigations in this issue [21, 22, 25]. Therefore, in this research, three models based on the Fig. 1 are created in the ABAQUS software to analyze the produced stresses in the welded joint due to the loading of rolling stock.

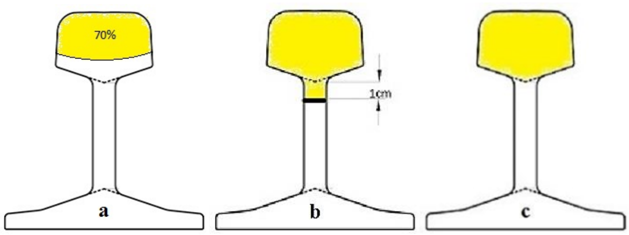

Figure 1
The yellow area shows the special electrode with abrasion resistance: a- 70% of the rail head, b- rail head and 1cm of web, c- the whole rail head area

3 Railway Loadings

The railway structure is subject to various forces. Since there is direct connection between the rail and the wheel, and the first component which is bearing the loads of rolling stock is the rail; all of loads are transferred by the rail to other components [26-30]. So, analyzing the various rail stresses, is the first step, in designing the railway track [8, 31-36].

One way to classify the forces applied to the rail is based on the direction of the force, which is divided into three categories of vertical, lateral (horizontal force and perpendicular to the track) and longitudinal forces (horizontal force and in the track direction) [37] [38]. These forces are shown in the Fig. 2.

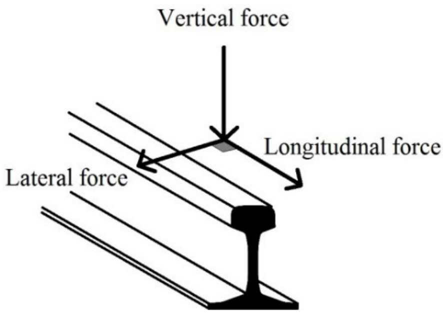

Figure 2
Different forces introduced by a wheel on a rail

Another method classifies the forces applied to the railway track into two categories of static and dynamic forces[39]. Static forces are mainly due to the weight of the railway vehicles, but it should be noted that since the rolling stock is passing over the rail and due to the existence of geometric and structural defects in the rails and in the railway vehicles, the nature of the vertical and lateral forces on the rail is dynamic [8, 40-47].

In this paper, the vertical and lateral forces are considered based on the railway track systems in Iran, and the longitudinal forces are ignored. The lateral forces on the rail are calculated based on the model calibrated by Sadeghi (2008) which is appropriate for the Iranian railway network [48]. The advantage of this model is that it is based upon the two parameters of velocity and the radius curve in the track. In this equation the curve radius is considered an infinite number since it has been presumed that the joint is located in the direct track and not in the curve[49, 51, 53]. This equation has been shown in the Eq. (3):

$$H = \left(\frac{1}{R}\right)(0.028V^2 + 7.62V + 4742.1) + V(1.34 \times 10^{-4}V + 0.036) + 22.43 \qquad (3)$$

H: Lateral load (kN)

V: Velocity (Km/h)

R: Radius curve (m)

The axle load of 22.5 tons is considered as the vertical force, which is the common axle load in the Iran's railway network. Therefore, the single wheel vertical static force is 11.25 tons. In order to consider the dynamic impacts of the railway vehicles, a dimensionless dynamic impact factor is multiplied by the vertical force.

The train wheels motion and the shocks caused by the movement of wheels on the uneven surface of rails are two main reasons for the dynamic nature of railway loading. There are various methods to calculate dynamic loads in the literature and it is performed by considering a dimensionless dynamic loading coefficient. In this research, Eq. (4), which is offered by AREMA, has been used to calculate the dynamic coefficient[49].

$$\varphi = 1 + 5.21\frac{V}{D} \tag{4}$$

V: Velocity (Km/h)

D: Wheel diameter (mm)

In Iranian railway network the passenger and freight trains are running simultaneously from the tracks which means that the tracks are designed to carry the loads coming from both passenger and freight trains[48]. The loading pattern on the railway track is considered as a mixture of axle load from wagons and locomotive. The axle load of wagons and locomotives of passenger trains are 12 and 22.5 tons respectively[48]. The axle load of freight trains is considered as 22.5 tons. Hence, the designation axle load in the railway tracks in Iran railway network is 22.5 tons. According to the Iranian Railways system, the train speed is 120 km/h and the wheel diameter for wagons and locomotive is 1000 and 1200 mm respectively. Consequently, the values of dynamic coefficients are 1.62 and 1.52, for wagon and locomotive respectively [51] [53]. A standard UIC 60 rail profile and concrete sleepers are assumed for the modeling. The distance between sleepers is considered 600 mm. It has been presumed that the joint is located in the direct track and not in the curve. Also, there is no longitudinal or lateral slope in the track. It has to be mentioned that the gravitational forces are simulated in the model due to the weight of the materials. After determining the vertical and lateral forces introduced on the rail, these forces are applied to the weld section in the model to analyze the weld and rail stresses at the joint.

4 Modelling of Railway Track

The modeling of a railway track and the welded joint has been performed based on finite element method (ABAQUS software). There are eight steps for creating a model of a railway structure. In the first step (part step), the geometry of the different components of railway structure is drawn. According to the common railway systems of the Iran's railway network, a UIC 60 rail profile and simple concrete sleepers are used in the model (Table 2).

Table 2
The properties of the rail in the finite element model

Rail geometric properties				
Rail type	**Head width (mm)**	**Height (mm)**	**Base width (mm)**	**Web thickness (mm)**
60E1 (UIC60)	72	172	150	16.5

Rail mechanical properties							
Rail type	**Rail steel hardness (MPa)**	**Yield stress (MPa)**	**Ultimate stress (MPa)**	**Allowable elongation (mm)**	**Poisson's ratio**	**Elastic modulus (GPa)**	**Specific mass (Kg/m^3)**
60E1 (UIC60)	900	580	1000	10	0.3	200	7854

Also, the joint between the two rail sections that is supposed to be filled with welding electrodes, is drawn separately. The width of the joint is considered as 10 mm. The joint is drawn in three different cases based on the patterns shown in Fig. 1. In the second step (property step), all the specifications and mechanical properties of the materials, including electrodes, rail and concrete sleepers, are assigned to the materials based on the standards and the relevant regulations (Table 3).

Table 3
The properties of the materials in the finite element model

Sleeper (B70) properties			
Sleeper type	**Fc (MPa)**	**Ft (MPa)**	**Section dimension (cm^2)**
Pre stressed B70	50	5	20 * 20

Electrode properties				
Electrode type	**Yield stress**	**Tensile strength**	**Elongation**	**Welding current**
ESAB OK 74.78	600 MPa	650 MPa	24%	DC+, AC
ESAB OK 83.28	650 MPa	------	24%	DC+, AC

In the assembly step, all components of the track structure are put together according to Fig. 3, and in the fourth step, the type of analysis is determined which is semi-dynamic. An essential aspect of the assembly process is to ensure that each component of the railway track is accurately positioned at the appropriate angle to facilitate reasonable interactions between elements such as the rail to sleeper and sleeper to ballast etc. In addition to the precise positioning of the railway track components during assembly step, it is also crucial that their dimensions are accurately defined to enable direct connections between them. This is particularly important in subsequent steps, such as the meshing process, where the components need to be securely interconnected to form a stable and functional railway track in the model. Also, the type of interaction between the materials is determined in the next step (interaction step), which means that the contact of the surface of the components including rail to sleeper and sleeper to ballast is defined in this step. The loading is assigned according to the Iran's railway network which has been discussed in the previous section. Boundary conditions are also considered in the load step, with proportional stiffness to simulate the ballast and subgrade layers under the sleepers [50].

Table 4
The properties of the ballast and sub-ballast in the finite element model

Item	E_b (MPa)	Φ (°)	Stiffness (KN/mm)
Ballast	250	20	25.53
Sub-ballast	150	35	25.53

To calculate the stiffness in the ballast, sub-ballast and subgrade, the ballast pyramid model has been used.[48, 52, 54]. In this research, stiffness of the ballast, sub-ballast and subgrade is calculated as 25.53 KN/mm which detail of the layers has been shown in Table 4. This stiffness is considered as the total stiffness under the sleeper and is implemented in the model.

The stress measurements are specifically focused on the part of the rail that lies between the sleepers. Referring to Fig. 3, it is observed that the blue section represents the welding point, while the orange section represents the rail's cross-section where the analysis is conducted. Mesh step is one of the most important parts of modeling and this module is for creating finite element meshes. In the mesh step the nodes, number of nodes and size of the elements of the track are defined. The nodes of the elements of the different components must have the necessary coordination with each other. The size of each component should be defined so that the number of elements is appropriate, which means that the number of elements will increase. This will increase the precision, but it should not cause any numerical errors.

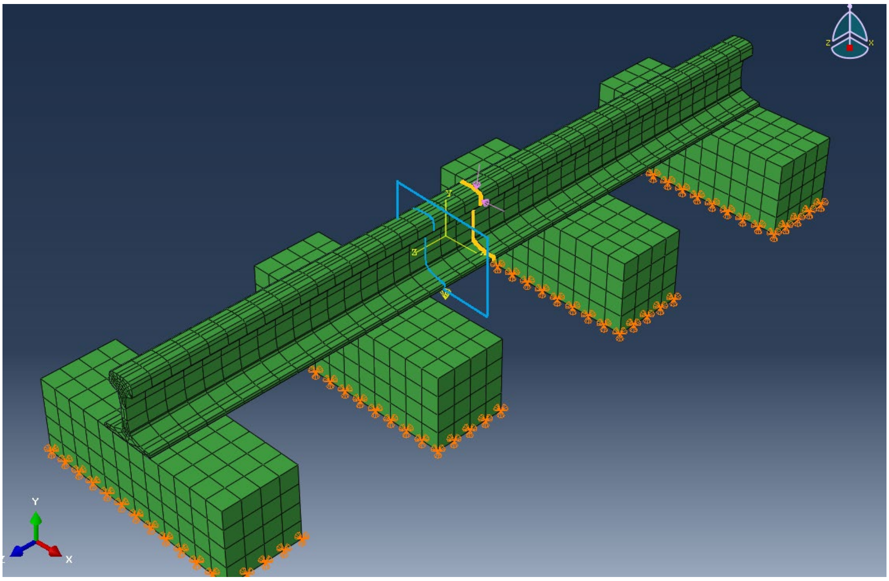

Figure 3
Finite element model

To ensure greater accuracy in the interaction between components and reduce the computational load, it is necessary for the size of the elements in the rail foot to be consistent with the size of the sleeper's upper surface. By maintaining the same dimensions, a more precise representation of the component interaction can be achieved, while simultaneously minimizing the volume of calculations required. Finally, according to the existing system, the analysis operation is performed and the results are extracted to be analyzed. As mentioned before, the model is created in three different cases for all the three patterns “a”, “b” and “c” according to Fig. 1; so, the analysis of the stresses in the rail and the welded joint, is performed three times.

5 Results and Discussion

5.1 Finite Element Analysis and Loading

The results of stress distribution in the welded joint and rail cross sections are shown in the Figures 5-7 ,based on the model created for the three different patterns “a”, “b” and “c”. The figures demonstrate two cross sections: one cross section exactly at the welded joint location; and the other cross section at the rail close to the welded joint.

The bending stresses caused by the vertical and lateral forces are calculated in 3 critical points at the rail, including rail head, the junction of rail head and web and the junction of rail web and foot in which there is stress concentration. The measured stresses are shown in Table 5.

Table 5
The measured stresses at 3 stress concentration zones in the rail

Measured point	**Stress (MPa)**		
	Pattern (a)	**Pattern (b)**	**Pattern (c)**
Rail head	153.48	169.30	155.06
Junction of rail head and web	142.41	142.40	142.41
Junction of rail web and foot	79.11	94.94	50.63

Since the stress concentration occurs at the junction of the rail head and web and also at the end of the rail foot, the stress value in these points has been investigated in the three patterns “a”, “b” and “c”. The results in the welded joint cross section for the patterns “a”, “b” and “c”; indicated that the maximum stress at the junction of the rail head and web occurred at the pattern “c” where the whole rail head has been welded by the abrasion resistant electrode. The lowest stress at the junction of the rail head and web in the welded cross section occurred at the pattern “b”, where the whole head and 1 cm of the web have been welded by the abrasion resistant electrode. The results demonstrated that the stress value decreased by 37% from pattern “c” to pattern “b” at the mentioned position. The stress value at the junction of the rail head and web for the pattern “a”, is similar to the pattern “c” according to Fig. 4 and Fig. 6. The results of stress analysis in the rail foot indicated that the pattern “c” achieved the best performance compared to other patterns. The maximum stress value in the pattern “c” for the rail foot decreased by 28% in comparison with stress value at the patterns “a” and “b”.

Regarding the results of modeling and the stress distribution at the rail cross section close to the welded joint, a negligible difference between the stress values of three patterns has been observed at the junction of the rail head and web. However, in the rail foot, the maximum stress value in pattern “c”, decreased by 21% compared to patterns “a”, and “b”, and the pattern “c” performed more properly than other patterns.

To validate the model, a comprehensive analysis was performed by comparing its outputs with previous studies. Specifically, the stress levels in the rail were evaluated and compared with those calculated in prior research based on relevant leaflets and standards. The results indicated that the stress values predicted by the model fell within a similar range as those obtained from previous studies, thus, confirming the model's accuracy and reliability in assessing rail stresses. [48, 49, 51, 53, 55].

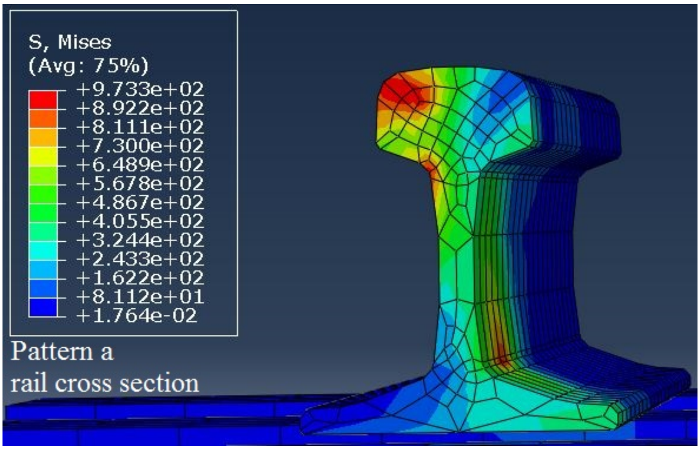

Figure 4
Stress distribution in the pattern "a"

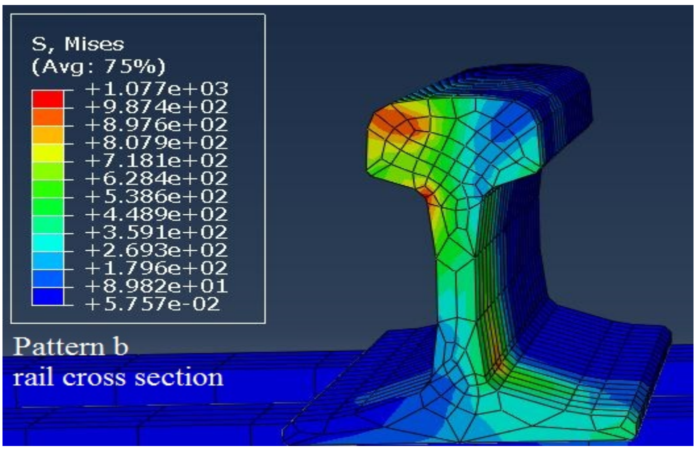

Figure 5
Stress distribution in the pattern "b"

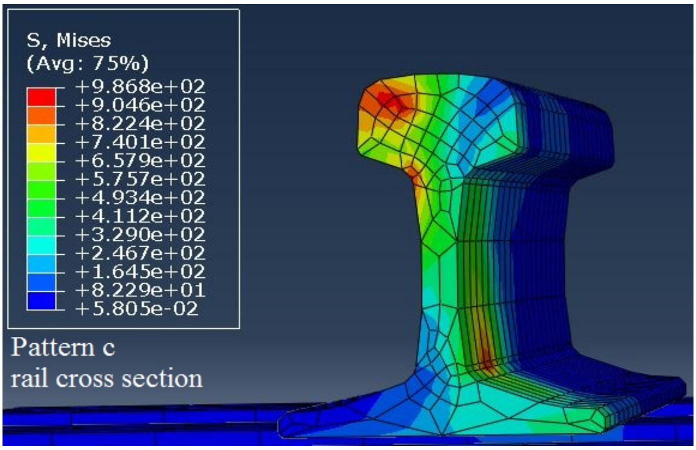

Figure 6
Stress distribution in the pattern "c"

5.2 Field Investigations

Based on the results of finite element modeling and the stress distribution in three patterns "a", "b" and "c" for a welded joint by narrow gap welding method, it is recommended to use pattern "b" as the most effective way of using electrodes in the narrow gap welding in Iran's railway network. The welding process of rail sections in Iran has been conducted by narrow gap welding method and using pattern "b" is shown in Fig. 7 (a).

The ultrasonic and portable hardness tests have been used to evaluate the performance of welded joints after the welding process. The outcome of the tests showed that the performance of welded joints was acceptable and the welding process has been done according to the recommended instructions. The procedure of ultrasonic test is demonstrated in Fig. 7 (b).

Although the narrow gap welding method is a new innovative way for rail joint welding, in its primary prototypes have had an acceptable performance and based on statistics and limited tests in railway track, it has been proven that it can be used on a large scale in the railway industry. An important aspect to highlight is the relatively new adoption of the narrow gap welding method within Iran's railway industry. Due to the limited knowledge and confidence surrounding its implementation, this welding technique has been utilized in only a few selected projects thus far. Consequently, there is a scarcity of information pertaining to the narrow gap welding method, necessitating further studies and research in the coming years. As the industry progresses, it is expected that increasing attention will be directed towards exploring and refining the potential of the narrow gap welding method, for railway applications in Iran.

Figure 7
(a) Welding process by narrow gap welding method (b) The ultrasonic test for rail welds

Conclusions

In the modern railway systems, the rail sections are welded together to form a Continuous Welded Rail (CWR) track. According to the predicted increase in train speed and axle loads, the use of CWR tracks could increase the safety and comfort of trains. There are different methods for welding the rails. Meanwhile, Narrow Gap Welding, is a common method in the construction and maintenance of railways, which has advantages, such as availability and lower costs. In the Narrow Gap Welding process, two types of electrodes are used with different stiffness; one electrode with abrasion resistance is used for the rail head and the other for the rail web and foot. In the current research a ESAB OK 74.78 electrode is considered for the rail web and foot, and an ESAB OK 83.28 electrode for the rail head. Due to the limitations of this welding method, the procedure concerning the use of the harder electrode in the rail head is less discussed. In this study, three different patterns for welding the rail head with harder electrode are investigated and modeled, based on a Finite Element Method (FEM). In the pattern "a", 70% of the rail head is welded by the harder electrode, in the pattern "b", the whole rail head plus 1 cm of the rail web is welded by the harder electrode and in the pattern "c", the whole rail head is welded by the harder electrode. The results of modeling and stress distribution in the mentioned patterns, indicated that in the welded joint, the stress value at the junction of the rail head and web in the pattern "b" is 37% less than the stress value at the same point in the patterns "a", and "c". Also in the rail foot, the maximum stress value in the pattern "c" is 70% of the maximum stress value of other patterns. According to the modeling results and analysis of existing stresses, it is recommended to use pattern "b", in the Narrow Gap Welding method.

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