Research Article

Meng He, Jianing Qi, Zhentai Zheng*, Fen Shi, and Yunfeng Lei

Numerical simulation of nickel-based alloys' welding transient stress using various cooling techniques

<https://doi.org/10.1515/htmp-2020-0067>

received August 02, 2019; accepted May 13, 2020

Abstract: Nickel-based alloys play an important role in the field of high-temperature alloys, which are widely used in nuclear reactors, aerospace and components of turbomachinery. However, the high susceptibility of welding hot crack is a main shortcoming to nickel-based alloys. One of the methods that reduce hot cracking susceptibility is by adjusting element constitution of weld metal and another method is by reducing transient stress. This article used finite element method to study the effect of cooling source on transient stress of the nickel-based alloy weld joint. The selection of appropriate cooling technique can decrease the peak of the transient von Mises stress and make the tensile stress turn into compressive stress, which is beneficial to reduce hot cracking susceptibility. The peak of the transient von Mises stress decreases as the cooling intensity increases from 0 to 15,000 W/m² K, but increases if the cooling intensity is ineffective. When the distance between cooling source and heat source reaches 35 mm, the weld can get larger region of compressive stress. The peak of the transient von Mises stress decreases with increasing radius of cooling source and reaches minimum value at 12 mm. Combined cooling is more effective in reducing the peak of this stress than the conventional single trailing cooling source.

Keywords: nickel-based alloys, hot cracking susceptibility, rapid cooling, finite element method, transient stress

1 Introduction

Nickel-based alloys are the most widely used superalloys for the applications requiring heat and corrosion resistance such as nuclear reactors, aerospace and components of turbomachinery. However, it has higher hot cracking susceptibility than carbon steel and stainless steel during welding. It is generally known that one of the cracking mechanisms in fusion zone (FZ) and heat affected zone (HAZ) is the low melting point eutectic formed by the segregation of alloying elements, and another important mechanism is the mechanical tensile stresses generated in the welding process. Because of the drastic change of temperature and stress in the welding process, the liquation film and low ductility metal in FZ and HAZ are stretched beyond their plastic strain range by tensile stresses, leading to the formation of hot cracks. Hence, there are two ways to reduce hot cracking susceptibility: adjusting weld metal compositions and reducing the tensile stresses of welding joint. Furthermore, the welding hot cracks of nickel-based alloy are caused during the cooling process of weld, and the residual stress appears on weld after the cooling process. Therefore, the peak value and distribution of the residual stress have no effect on hot cracks. This means that transient stress in the welding process is very essential to reduce hot cracking susceptibility but not the residual stress.

Ren et al. [1] found that the continuous (Cr, Mo)-rich phase decreased as the heat input and preheating temperature increased in the fiber laser welding of Inconel 617. Vishwakarma and Chaturvedi [2] revealed that the HAZ grain boundary liquation of Allvac 718 Plus was caused by the segregation of the minor alloying elements of Saida et al. [3] have reported that ductility dip cracking in multilayer weld metal of alloy 690 can be attributed to grain boundary segregation of P and S. Mo et al. [4] found that boron segregated at grain boundaries in NiCrFe-7 weld metal, and the boron promoted the formation of

* **Corresponding author: Zhentai Zheng**, School of Materials Science and Engineering, Hebei University of Technology, No. 8, Guangrongdao Road, Hongqiao District, Tianjin 300130, People's Republic of China, e-mail: zzt@hebut.edu.cn

Meng He, Jianing Qi, Fen Shi, Yunfeng Lei: School of Materials Science and Engineering, Hebei University of Technology, No. 8, Guangrongdao Road, Hongqiao District, Tianjin 300130, People's Republic of China

continuous M₂₃(C, B)₆ carbide chains and M₂B borides along grain boundaries, which causes more ductility-dip-cracking (DDC) in the weld metal. Osoba *et al.* [5] studied microstructures of Haynes 282 nickel-based alloys with laser welding and found that carbon has inhibitory effect on the formation of eutectic γ - γ' , which results in solidification cracking. Ramirez and Lippold [6] found that C, Nb and Ti can form bending grain boundaries when enough medium size (Nb,Ti)C eutectic phase is generated. Such boundaries were less prone to sliding and were beneficial to resist DDC cracking. Chamanfar *et al.* [7] found that the segregation and γ' dissolution in FZ and HAZ are the mechanisms for cracking.

It is obvious that most of those researchers paid more attention to the effect of alloying element on the hot cracking sensitivity of nickel-based weld alloy. However, adjusting alloying element can only reduce the hot cracking susceptibility of weld and cannot reduce the hot cracking susceptibility of HAZ. Therefore, it is necessary to take appropriate measures to reduce the hot cracking susceptibility of weld and HAZ by reducing transient stress at the same time. Cooling technique is regarded as an effective method to achieve this goal.

Manikandan *et al.* [8] found that the enhanced cooling rate with liquid nitrogen reduced the interdendritic phases, and the dendrite arm spacing was reduced from the range of 15–54 to 3–17 μm during the gas tungsten arc welding (GTAW) process. Jiang *et al.* [9] found that the heat sink technology can decrease the residual stress greatly, and with the average heat transfer coefficient increase, the transverse stress is decreased greatly. Transverse tensile stresses have been changed to compressive in some zones. Yegaie *et al.* [10] found that the heat sink can limit the high-temperature region to the vicinity of heat source and decrease the maximum temperature of the sample, which result in lower residual stresses and even compressive stresses near the weld zone. Li *et al.* [11,12] further studied the effect of distance between cooling source and heat source on residual stress by controlled low stress non-deformation technique and found that there exists an appropriate distance in which the residual stress and plastic strain were both well controlled. Kala *et al.* [13], Zhang *et al.* [14] and Bajpei *et al.* [15] also studied the effect of cooling source on residual stress and deformation using different materials with various coolants.

In the previous research studies, most of the researchers paid attention to the effect of cooling technique on the residual stress and ignored the effect of cooling technique on transient stress. However, transient stress plays an important role in reducing the hot cracking sensitivity of nickel-based weld but not residual stress. Therefore,

in this study, the effect of cooling technique in reducing the transient stress and playing down the hot crack sensitivity of nickel-based weld is discussed.

2 Finite element model

A three-dimensional finite element model was developed by ANSYS to simulate the transient stress in the process of welding with rapid cooling. First, thermal analysis was performed to calculate the temperature histories. Then the temperature results were applied to the mechanical model to simulate the transient stress by the indirect coupling method.

2.1 Finite element mesh

Nicrofer 6023H (i.e., UNS N06601) sheets were butt welded together with the dimension of 100 mm $\times$ 60 mm $\times$ 4 mm. The weldments were symmetrical from weld center line; so only half of the sheets were selected as a simulation model to reduce the calculation cost. In total, 17,697 nodes and 11,891 elements were meshed. Solid70 and solid90 were selected as element types and used for temperature field analysis in different areas. Because the weld metal changed drastically in the actual welding process, a finer mesh with length 1 mm was used in the finite element model in weld zone, and the element size increased gradually from weld center line to the edge of sheet. The finite element mesh is shown in Figure 1.

2.2 Material properties

The solidus temperature of Nicrofer 6023H is 1,320°C and the liquidus temperature is 1,370°C. The temperature-dependent physical properties and mechanical properties referenced to the specifications of Nicrofer 6023H published by ThyssenKrupp VDM. Because the specifications published by ThyssenKrupp VDM can only provide thermal and physical properties, mechanical parameters in the temperature range are lower than melting point and the parameters in high temperature are difficult to obtain, an extrapolation method was used to define a reference value when the temperature was higher than the melting point. Furthermore, the finite element model in this article only took the latent heat of fusion and solidification into consideration.

Figure 1: Finite element mesh.

2.3 Heat source and heat dispersion model

In thermal analysis, a moving heat source based on the double ellipsoidal heat source model proposed by Goldak et al. [16] and Goldak and Akhlaghi [17] was applied to simulate the heat provided by welding torch in the GTAW process. The volumetric power density distribution of the front half is as follows:

$$q(x, y, z) = \frac{6\sqrt{3}f_f q_0}{abc_f \pi \sqrt{\pi}} \exp\left(-\frac{3x^2}{c_f^2} - \frac{3y^2}{a^2} - \frac{3z^2}{b^2}\right). \quad (1)$$

The volumetric power density distribution of the rear half is as follows:

$$q(x, y, z) = \frac{6\sqrt{3}f_b q_0}{abc_b \pi \sqrt{\pi}} \exp\left(-\frac{3x^2}{c_b^2} - \frac{3y^2}{a^2} - \frac{3z^2}{b^2}\right), \quad (2)$$

where a , b , c_f and c_b are the shape parameters that determine the size of weld pool, q_0 is the effective heat input and f_f and f_b are the fractions of the heat deposited in the front and rear half where $f_f + f_b = 2$. Here it is assumed that f_f is 0.6 and f_b is 1.4. The number “3” is the actual heat flux distribution parameter, which characterizes the concentration level of heat flux distribution. The distribution of double ellipsoidal heat source model is shown in Figure 2.

Figure 3 shows the schematic diagram of GTAW with cooling source as an example of the rapid cooling technique in this article. Liquid nitrogen was selected as the coolant because (a) of high cooling efficiency and (b) nitrogen does not harm the nickel-based alloy weld. The liquid nitrogen was squeezed out from a container by a pneumatic device into a copper pipe, which is named cooling pipe. In position 1, the cooling pipe is

Figure 2: Double ellipsoidal heat source model.

located 10 mm above the surface of weldment parallel to the weld direction trailed with a welding torch. In position 2, the cooling pipe is below the surface of weldment parallel to the weld direction and 10 mm distant from the surface.

To simulate the rapid cooling effect in the finite element analysis, the average heat transfer coefficient was calculated by the following expression introduced by Martin [18]:

$$\bar{h} = \frac{k\bar{Nu}}{D}, \quad (3)$$

where k is the thermal conductivity of liquid nitrogen, $\bar{Nu}$ is the average Nusselt number and D is the equivalent cooling Pipe diameter. $\bar{h}$ is applied as the condition of radiation over the nodes in which the cooling is applied.

Figure 3: Schematic diagram of GTAW with trailing cooling source.

2.4 Other heat boundary conditions and mechanical constraints

In thermal analysis, the ambient temperature was defined as 20°C, and the convection and radiation heat transfer coefficient, h , was applied to all surfaces except for square groove face, as well as over the surfaces exposed to heat and cooling sources. The convection and radiation heat transfer coefficient was given by the following equivalent expressions in total form introduced by Deng and Murakawa [19]:

$$h = 0.0668T \quad 0 < T \leq 500^\circ\text{C}, \quad (4)$$

$$h = 0.231T - 82.1 \quad T > 500^\circ\text{C}. \quad (5)$$

It is important to select an appropriate set of displacement constraints. When the stress field was simulated, the rigid displacement of weldment must be limited to release the thermal strains which will slow down the convergence considerably. The welding situation changed with time irregularly, and so a nonlinear analysis was needed. In addition, the upper limit of the number of equilibrium iterations was increased, and a linear search was activated together with the Newton–Raphson method to ensure the convergence of whole stress field simulation process. For the purpose of avoiding stress concentration and making sure that there is no rigid displacement, the following constraints were used: area 3 is imposed on symmetry constraint, line 2 is constrained in the Z-direction and keypoint 1 is constrained in the X-direction as shown in Figure 4.

Figure 4: Constraints of mechanical model in simulation of welding transient stress.

Table 1: Parameters of Nicrofer 6023H GTAW process

Parameters	Value
Arc voltage (V)	12
Welding current (A)	140
Welding speed (mm/s)	2
Thermal efficiency	0.7

3 Model validation experiment

It is too difficult to measure the transient stress by instruments. Moreover, the transient stress is caused by temperature's uneven distribution. In other words, the distribution of temperature determines the transient stress. Therefore, the simulated and experimental temperature histories were compared to validate the thermal model in this article. The corresponding experiment was carried out by a welding machine of Panasonic YC300WX N type and an automatic welding device. Two sheets of Nicrofer 6023H were placed on the welding platform with dimensions of 100 mm × 60 mm × 4 mm. The parameters of the welding process are summarized in Table 1.

Three K-type thermocouples were used as the temperature measurements and placed as shown in Figure 5. The temperature histories were recorded by a data acquisition instrument of TOPTEST TP99080324. As can be seen from Figure 6, the experimental temperature histories of point A ($x = 30$ mm, $y = 10$ mm and $z = 2$ mm), point B ($x = 50$ mm, $y = 13$ mm and $z = 2$ mm) and point C ($x = 70$ mm, $y = 16$ mm and $z = 2$ mm) agreed with the simulation results.

Figure 5: Schematic diagram of temperature measurement in the GTAW process.

Figure 6: Comparison of experimental and simulated temperature histories in GTAW process: (a) point A; (b) point B and (c) point C.

4 Results and discussion

In the welding of nickel-based alloys, alloy elements segregate in particular at grain boundaries and form low melting point phases such as eutectic $\gamma-\gamma'$, Laves phase and MC carbides along solidified grain boundaries. The presence of intergranular liquid films results in micro-fissure because the liquid films cannot withstand the thermal and mechanical tensile stresses in the GTAW process. Consequently, solidification cracking and liquation cracking occur by the solid-liquid interface separation in brittle temperature range (BTR), which is lower than the melting point of nickel-based alloys. It is one of the critical factors of high hot cracking susceptibility. Besides, there is a ductility dip temperature range (DTR) between solidus temperature (T_s) and $0.5T_s$. The weld is in

low ductility in this temperature range and easy to crack under tensile stresses, inducing the formation of DDC. The BTR and DTR are shown in Figure 7.

With the aim of investigating the effect of rapid cooling on hot cracking susceptibility in the nickel-based alloy weld, the transient von Mises stress in the temperature range of 1,350–550 °C was discussed.

4.1 Effect of cooling intensity on transient stress

To analyze the effect of cooling intensity on GTAW temperature field, the temperature histories of the points $x = 50$ mm, $y = 0$ mm and $z = 4$ mm under different cooling

Figure 7: Schematic diagram of ductility as a function of temperature.

intensities were investigated, and the results are shown in Figure 8. It is clearly shown that the node under cooling source undergoes two heating cycles. The heating cycle between 20 and 50 s was caused by the weld heating itself, and the other between 50 and 150 s was caused by the surrounding zones. The cooling source cannot decrease the maximum temperature, but can increase the cooling rate. The cooling rate was increased gradually with the cooling intensity, reaching a maximum at $15,000 \text{ W/m}^2 \text{ K}$, and then it was kept stable even if the cooling intensity increases to $20,000 \text{ W/m}^2 \text{ K}$.

The nickel-based alloys could be sensitized in $1,350\text{--}550^\circ\text{C}$, which will lead to the hot crack susceptibility of nickel-based alloys weld. It is very important to decrease the dwell time in $1,350\text{--}550^\circ\text{C}$. In the case of cooling with

a cooling source, it took similar time to cool from $1,350$ to $1,200^\circ\text{C}$ compared to that without a cooling source, but it took less time to cool from $1,200$ to 550°C when the cooling source was used. This means the dwell time around the BTR and the DTR decreases a lot. It is obviously shown that the cooling source is helpful in decreasing the risk of sensitization of the nickel-based alloy weld, leading to a decrease in the hot cracking susceptibility.

Figure 9 shows the temperature distributions and isotherms of conventional welding and welding with trailing cooling source when $t = 30 \text{ s}$. It can be found that the high-temperature region was limited to the vicinity of heat source and a low-temperature zone formed in the weld. This indicates that lower hot stresses have formed in the period of GTAW with trailing cooling source.

The simulated transient von Mises stress for different cooling intensities is shown in Figure 10. The transient von Mises stress had a little difference between the various cooling intensities and without cooling source in the temperature range of $1,350\text{--}1,200^\circ\text{C}$. That is because they had the same cooling rate that can be seen in Figure 8. However, in the temperature range of $1,200\text{--}550^\circ\text{C}$, the model with cooling source had lower transient von Mises stress than that without cooling source. Furthermore, a little difference was found between the various cooling intensities in the temperature range of $1,200\text{--}1,000^\circ\text{C}$ because of the same cooling rate that can be seen in Figure 8. However, the transient von Mises stress decreased obviously from $1,000$ to 550°C as the cooling intensity increases from $4,000$ to $15,000 \text{ W/m}^2 \text{ K}$, and then it remained stable even if the cooling intensity reaches $20,000 \text{ W/m}^2 \text{ K}$. This is mainly because of the shrinkage of the metal in the quench zone, which causes the pressure on the front metal. The compressive stress produced by this extrusion can largely offset the tensile stress which was benefit to reduce the hot cracking susceptibility.

Figure 11 shows the transverse stress distributions along weld center line of different cooling intensities at $t = 30 \text{ s}$. At this moment ($t = 30 \text{ s}$), the heat source is moved to the place where $x = 60 \text{ mm}$, and the cooling source is moved to the place where $x = 45 \text{ mm}$. The transverse stresses of weld metal between cooling source and heat source were mainly investigated. The weld metal near the cooling source acted shrinks more rapidly as the cooling intensity increases. Hence, the transverse stresses became higher and even increased to approximately 600 MPa when the cooling intensity is $20,000 \text{ W/m}^2 \text{ K}$. Setting cooling intensity to $15,000$ and $20,000 \text{ W/m}^2 \text{ K}$ was only for the purpose of finding out the change rule of transient stress and compression to the metal between cooling source and heat source under limited conditions, which is difficult to

Figure 8: Effect of cooling intensity on temperature histories.

Figure 9: 3D simulated temperature fields and isotherms of conventional GTAW and GTAW with trailing cooling source. (a) Temperature field of conventional welding; (b) temperature field of welding with trailing cooling source; (c) isotherms of conventional welding and (d) isotherms of welding with trailing cooling source.

achieve in the actual experiments. In the case without the cooling source, the transverse stress of weld metal from $x = 45$ mm to $x = 60$ mm was tensile and increased gradually. However, in the case with the cooling source, the cooling source changed the transverse stress from tensile to compressive. This is mainly because the weld metal near cooling source grinds against front meal. Moreover, it is obvious that the transverse compressive stress produced by this extrusion is helpful to play down the hot crack susceptibility. Furthermore, with the increase in cooling intensity, the compressive stress between $x = 45$ mm and $x = 50$ mm increased and there is no change in the compressive stress from $x = 50$ mm to $x = 60$ mm. That is because the cooling rate is increased with the increase in cooling intensity, and the compressive stress induced by the rapid cooling becomes stronger. This is consistent with the change of the transient von Mises stress in different temperature ranges in Figure 10. It can be concluded that the cooling source can change the transverse stress from

Figure 10: Effect of cooling intensity on the transient von Mises stress.

Figure 11: Transverse stress distributions along weld center line of different cooling intensities when $t = 30$ s.

tensile stress to compressive stress and improve the resistance to hot cracking. There is an appropriate value of cooling intensity, which is $15,000 \text{ W/m}^2 \text{ K}$ in this article.

4.2 Effect of distance between cooling source and heat source on transient stress

During GTAW with trailing cooling source, the compression induced by rapid cooling may change with the distance between cooling source and heat source, D_{is} . Figure 12 shows the effect of D_{is} on the transient von Mises stress at the point $x = 50 \text{ mm}$, $y = 0 \text{ mm}$ and $z = 4 \text{ mm}$.

The model without cooling source can be seen as D_{is} toward infinity. It is shown that the difference in the D_{is} does not change the transient von Mises stress in the temperature range of $1,350\text{--}1,200^\circ\text{C}$. That is because that the weld metal has the same cooling rate in the temperature range of $1,350\text{--}1,200^\circ\text{C}$ even if the D_{is} is different. In the temperature range of $1,200\text{--}550^\circ\text{C}$, the model with cooling source had lower transient von Mises stress than that without cooling source. When D_{is} was 15 mm , because of the strong cooling effect and the smallest distance, the transient von Mises stress decreased to the lowest level of four different distances in the temperature range of $1,200\text{--}970^\circ\text{C}$. As D_{is} is increased, metal compression between cooling source and heat source became weaker and the decrease in von Mises stress became less obvious. However, with the increase in the D_{is} , the von Mises stress decreased gradually and reached the bottom when D_{is} is 35 mm , and then it increased in the temperature range of

$680\text{--}550^\circ\text{C}$. The most potent D_{is} that reduces the transient von Mises stress at the range of different temperatures is different.

The transverse stress distributions along weld center line of different D_{is} at $t = 30 \text{ s}$ are shown in Figure 13. At this moment ($t = 30 \text{ s}$), the heat source is moved to the place where $x = 60 \text{ mm}$. The transverse stress of weld metal was tensile stress and increased gradually from $x = 45 \text{ mm}$ to $x = 60 \text{ mm}$ when D_{is} is infinity. With the decrease in the D_{is} , the cooling source changed the transverse stress from tensile to compressive. This is because the cooling source increases the cooling rate of weld metal which is near the cooling source, which causes the compression. The value of compressive stress

Figure 12: Effect of distance between cooling source and heat source on the transient von Mises stress.

Figure 13: Transverse stress distributions along weld center line of different distances between cooling source and heat source when $t = 30$ s.

between $x = 45$ mm and $x = 60$ mm reached to maximum when the D_{is} is 25 mm. When the D_{is} decreases from 35 to 15 mm, the compressive stress between $x = 45$ mm and $x = 55$ mm decreased first and then increased, and the compressive stress between $x = 55$ mm and $x = 60$ mm increased. Furthermore, the compression zone became wider as the D_{is} increased from 15 to 35 mm. Hence, the distributions of the compressive stresses extended to a wider range on weld metal, which is helpful to reduce hot cracking susceptibility.

The above results indicated that appropriate D_{is} can reduce the transient von Mises stress, change the transverse tensile stress to transverse compressive stress and wide the compressive stress region. The transient von Mises stress and transverse stress were taken into consideration. The appropriate value of D_{is} is 35 mm.

4.3 Effect of radius of trailing cooling on transient stress

There are few investigations into the effect of radius of trailing cooling, r , on transient stress. Therefore, a simulation experiment was conducted under the condition of $D_{is} = 15$ mm to investigate the change of transient von Mises stress for different r in the welding process. Figure 14 shows the transient von Mises stress at points $x = 50$ mm, $y = 0$ mm and $z = 4$ mm for different r .

The model without cooling source can be seen as r toward infinitesimal. It is shown that the difference in the r does not change the transient von Mises stress in the temperature range of 1,350–1,200°C. With the increase in r , the transient von Mises stress decreased gradually,

reaching a minimum at 12 mm, and then it kept stable in the temperature range of 1,200–550°C. Furthermore, in this temperature range, the weld metal was in a state of low ductility, and the decrease in the instantaneous von Mises stress can reduce the degree of stretching of the liquid film, which is beneficial to reduce the occurrence of hot cracking of the nickel-based alloy weld.

The transverse stress distributions along the weld center line of different r when $t = 30$ s are shown in Figure 15. At this moment ($t = 30$ s), the heat source moved to the place where $x = 60$ mm, and the cooling source moved to the place where $x = 45$ mm. It is obvious that the transverse stresses exist in the form of compressive stresses between $x = 45$ mm and $x = 60$ mm. However, the transverse stresses changed very little as r increased. As the connection between von Mises stress and principal stresses on three directions was complicated, there may be other factors that affected cooperatively with the compression induced by rapid cooling to reduce the transient von Mises stress.

The above results indicate that the transient von Mises stress decreases most when r increases to 12 mm. The capability of reducing von Mises stress and hot cracking susceptibility improves little when r is larger than 12 mm.

4.4 Effect of combined cooling source on transient stress

In order to research the effect of combined cooling source on hot cracking susceptibility of nickel-based alloy weld, two cooling ways were discussed as shown in Figure 3.

Figure 14: Effect of radius of trailing cooling source on the transient von Mises stress.

Figure 15: Transverse stress distributions along weld center line of different radii of trailing cooling source when $t = 30$ s.

One of the methods is that the liquid nitrogen just flows into the cooling pipe located in position 1, and the other way is that the liquid nitrogen flows into two cooling pipes located in positions 1 and 2.

Figure 16 shows the effect of different cooling methods on von Mises stress. From Figure 16, it can be seen that the transient von Mises stress had little change even if the cooling way changes in the temperature range of 1,350–1,200°C. In the temperature range of 1,200–550°C, the von Mises stress decreased to a lower level with the combined cooling source than others. This means that the combined cooling source has a better effect than welding with a single trailing cooling source on the control of transient stress and hot cracking susceptibility. Combined cooling source provided one more orientation of radiation for weld metal than the single trailing cooling source. This increased the cooling rate of weld metal which was helpful to reduce the transient stress and hot cracking susceptibility.

As can be seen from part (a) of Figure 17, the microstructures of weld center are almost large columnar grain structure. When the sheets were welded with the single trailing cooling source, the grains got refined and the coarse columnar grains were changed into equiaxed grains. In addition, comparing (b) and (c) of Figure 17, it can be observed that the grains became finer when the sheets were welded with the combined cooling source. Combined cooling source provided one more orientation of radiation for weld metal than the single trailing cooling source, which resulted in the cooling rate increases. Furthermore, with increasing cooling rate the undercooling of weld increased, which caused grain refinement. This confirmed that the combined cooling

Figure 16: Effect of different cooling methods on the transient von Mises stress.

source can reduce the hot cracking susceptibility of nickel-based alloy weld joints through adjusting metallurgical and stress factors.

5 Conclusions

In this article, the effect of cooling source parameters on the transient von Mises stress and hot cracking

Figure 17: Microstructures of weld with different positions of cooling pipe. (a) Conventional welding; (b) single trailing cooling and (c) combined cooling.

susceptibility of Nicrofer 6023H sheets was investigated by numerical simulation. Conclusions of this investigation are as follows:

- (1) Under the single trailing cooling source, the transient von Mises stress first decreases, and then increased with the increase in the cooling intensity and reaches the minimum value at $15,000 \text{ W/m}^2 \text{ K}$. The transverse tensile stress turns into compressive stress, and the weld has the lowest susceptibility to hot crack when the cooling intensity reaches $15,000 \text{ W/m}^2 \text{ K}$.
- (2) Under the single trailing cooling source, the most potent D_{is} that reduces the transient von Mises stress at the range of different temperatures is different. However, the width of the zone of the transverse compressive stress reaches maximum when D_{is} is 35 mm. This D_{is} has a better effect in reducing the transient von Mises stress and hot cracking susceptibility.
- (3) Under the single trailing cooling source, with the increase in r from 4 mm to 16 mm, the transient von Mises stress first decreases, and then keeps stable and reaches minimum when r is 12 mm.
- (4) The combined cooling source has a better effect than the single trailing cooling source on the control of transient stress in the welding process and hot cracking susceptibility. Combined cooling source can reduce the hot cracking susceptibility of nickel-based alloy weld joints by adjusting metallurgical and stress factors.

Acknowledgments: The authors gratefully acknowledge the financial support by the Natural Science Foundation of Hebei Province, P.R. China under Grant No. E2017202011.

References

- [1] Ren, W., F. Lu, R. Yang, X. Liu, and Z. Li. Liquation cracking in fiber laser welded joints of Inconel 617. *Journal of Materials Processing Technology*, Vol. 226, 2015, pp. 214–220.
- [2] Vishwakarma, K. R., and M. C. Chaturvedi. Effect of boron and phosphorus on HAZ Microfissuring of Allvac 718 Plus superalloy. *Materials Science and Technology*, Vol. 25, 2009, pp. 351–360.
- [3] Saida, K., Y. Nomoto, H. Okauchi, H. Ogiwara, and K. Nishimoto. Influences of phosphorus and sulphur on ductility dip cracking susceptibility in multipass weld metal of alloy 690. *Science and Technology of Welding and Joining*, Vol. 17, 2012, pp. 1–8.
- [4] Mo, W., X. Hu, S. Lu, D. Li, and Y. Li. Effects of boron on the microstructure, ductility-dip-cracking, and tensile properties for NiCrFe-7 weld metal. *Journal of Materials Science Technology*, Vol. 31, 2015, pp. 1258–1267.
- [5] Osoba, L. O., R. G. Ding, and O. A. Ojo. Microstructural analysis of laser weld fusion zone in Haynes 282 superalloy. *Materials Characterization*, Vol. 65, 2012, pp. 93–99.
- [6] Ramirez, A. J., and J. C. Lippold. High temperature behavior of Ni-base weld metal Part II-Insight into the mechanism for ductility dip cracking. *Materials Science and Engineering A*, Vol. 380, 2004, pp. 245–258.
- [7] Chamanfar, A., M. Jahazi, A. Bonakdar, E. Morin, and A. Firoozraia. Cracking in fusion zone and heat affected zone of electron beam welded Inconel-713LC gas turbine blades. *Materials Science and Engineering A*, Vol. 642, 2015, pp. 230–240.
- [8] Manikandan, S. G. K., D. Sivakumar, K. P. Rao, and M. Kamaraj. Microstructural characterization of liquid nitrogen cooled Alloy 718 fusion zone. *Journal of Materials Processing Technology*, Vol. 214, 2014, pp. 3141–3149.
- [9] Jiang, W. C., Y. C. Zhang, and W. Woo. Using heat sink technology to decrease residual stress in 316L stainless steel welding joint: finite element simulation. *International Journal of Pressure Vessels and Piping*, 2012, Vol. 92, pp. 56–62.

- [10] Yegaie, Y. S., A. Kermanpur, and M. Shamanian. Numerical simulation and experimental investigation of temperature and residual stresses in GTAW with a heat sink process of Monel 400 plates. *Journal of Materials Processing Technology*, Vol. 210, 2010, pp. 1690–1701.
- [11] Li, J., Q. Guan, Y. W. Shi, and D. L. Guo. Stress and distortion mitigation technique for welding titanium alloy thin sheet. *Science and Technology of Welding and Joining*, Vol. 9, 2004, pp. 451–458.
- [12] Li, J., Q. Guan, Y. W. Shi, D. L. Guo, Y. Du, Y. Sun, et al. Effects of distance between arc and heat sink on stress and distortion in DC-LSND welding technology. *China Welding*, Vol. 16, 2007, pp. 6–9.
- [13] Kala, S. R., N. S. Prasad, and G. Phanikumar. Studies on multipass welding with trailing heat sink considering phase transformation. *Journal of Materials Processing Technology*, Vol. 214, 2014, pp. 1228–1235.
- [14] Zhang, Y., Y. Ying, X. Liu, and H. Wei. Deformation control during the laser welding of a Ti6Al4V thin plate using a synchronous gas cooling method. *Materials and Design*, Vol. 90, 2016, pp. 931–941.
- [15] Bajpei, T., H. Chelladurai, and M. Z. Ansari. Mitigation of residual stresses and distortions in thin aluminium alloy GMAW plates using different heat sink models. *Journal of Manufacturing Processes*, Vol. 22, 2016, pp. 199–210.
- [16] Goldak, J., A. Chakravarti, and M. Bibby. A new finite element model for welding heat sources. *Metallurgical Transactions B*, Vol. 15, 1984, pp. 299–305.
- [17] Goldak, J., and M. Akhlaghi. *Computational welding mechanics*. Springer Science & Business Media, US, 2006, pp. 29–34.
- [18] Martin, H. Heat and mass transfer between impinging gas jets and solid surfaces. *Advances in Heat Transfer*, Vol. 13, 1977, pp. 1–60.
- [19] Deng, D., and H. Murakawa. Numerical simulation of temperature field and residual stress in multi-pass welds in stainless steel pipe and comparison with experimental measurements. *Computational Materials Science*, Vol. 37, 2006, pp. 269–277.