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Exergy analysis; the practical method for investigating the effect of parallel heating on welding residual stresses

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Abstract

In this paper, analytical relations of energy and exergy efficiency are written for GMA welding. Then the effects of parallel heating on these two efficiencies are checked. The difference between these two efficiencies is due to welding processes irreversibility. Residual stresses are type of irreversibility. So, the effect of parallel heating on welding residual stresses are checked by difference between these two efficiencies (dimensionless entropy).Flame heating are assumed as point and spot heat sources. Also, it is shown that the temperature distribution is quasi-steady. What's more, a parameter is introduced as a ratio of exergy efficiency to energy efficiency that it can help to investigate the amount of cost saving for parallel heating process. The results are adopted with data sources. The results show that by increasing flame power, energy and exergy efficiency will decrease, while; the slope of these efficiencies decreases gradually. In addition, increasing the speed of welding is caused to rise up both efficiencies. Dimensionless entropy decreases because of increasing the internal flames heat. It demonstrates that decreasing the residual stresses are due to welding. This reduction is greater at higher speeds. So, parallel heat at higher speed is more effective to increase the welding quality. As well as, the ratio of two efficiency shows that the heating about 1800 j/s would be economically optimal amount. Finally, considering the results with previous data, use of dimensionless entropy generation for checking the residual stresses of welding has recommended.

Keyword

Parallel heating, energy efficiency, exergy efficiency, welding residual stresses, entropy generation

Introduction

The most important factors in the amount of residual stresses are characteristics of welding flame and thermal gradients that investigating in the way of increasing the welding quality shows this issue. So, the several researches are done about the effects of the temperature distribution and the form of melting pool on the amount of welding residual stresses. In 1998, Liang Tenga et al surveyed the effect of speed of cooling piece on the amount of welding residual stresses by the finite element method. In addition, they proved that increasing the cooling speed is caused to rising up the welding residual stresses [1]. In 2006, Sunar et al showed that the thermal gradients do not have much effect on the residual transverse [2]. In 2009, Kiyoshima et al used the various models of heat flux to simulate the welding flame. Also, they studied the effects of each one on the residual stresses [3]. In addition, the different methods have been proposed to decrease thermal gradients and welding residual stresses. In 2012, Jiang et al used heat sink technology to make the desired changes for determination of thermal gradients of weld bond. Thereby, they were able to decrease the amount of residual stresses, up to 20% [4]. Another method is that using two moving flame which was moved parallel to weld flame. In 1995, Lin was a person who firstly used this method [5] and we use it in this study. He showed by the experimental results that we can reduce residual stresses 21% _ 32% by using the parallel heating. In 2011, Barsanescu et al showed via drilling method that by using the discussed technique, the VON MISES stresses are decreased, up to 70% in a number of welding pieces [6].

In recent years, discussion of welding thermodynamics to increase welding quality has been considered [7]. In 2008, Alqahtani studied the effect of pulse laser parameters on entropy generation rate [8]. Relationship between irreversibility(entropy generation) and welding residual stresses were offered by Falahi et al ,in 2011[9].In that article, considering to the equation of entropy generation according to temperature distribution, the effect of the welding sequence on amount of welding residual stresses was evaluated. In this article, analytical relationships of energy and exergy efficiencies for arc welding have written. Also, the effect of parallel heating and speed welding on both above efficiency has evaluated. The difference between these two efficiencies is because of irreversibility in the weld process or entropy generation in it. Residual stress is the most important reason for irreversibility [10, 11]. So, changes in the difference between two efficiencies because of parallel heating show the changes in residual stress pieces. In addition, a parameter has introduced as ratio of two efficiencies. As well as, we can determine optimized heating by using this parameter.

Physics of the subject

In Figure 1, heat transfer processes and mass transfer in arc welding has shown. According to Figure 1, the amount of energy generation by electrical current has waste by 3 mechanism: conduction, convection and radiation. Also, the great amount of it is caused to produce the metal of welding bond. In adition, the little amount of it is consumed to evaporate metal. In this study, the piece is in the initial temperature (T_{pr}) as the same of initial temperature of welding bond. If the welding bond is assumed as volume control, energy will be entered to volume control via flame. It is caused to increase the temperature of it. Finally, it melts while; farther areas temperature is assumed approximately equal to initial temperature of piece. Then, melted metal is freeze slowly. Also, it loses heat through conduction, radiation and convection. Cooling is continued up to the initial temperature of piece that it is final point of problem study. Here, we assume that pieces temperature is uniform and equal to T_{pr}. Figure 2 shows the usage of parallel heating in welding.

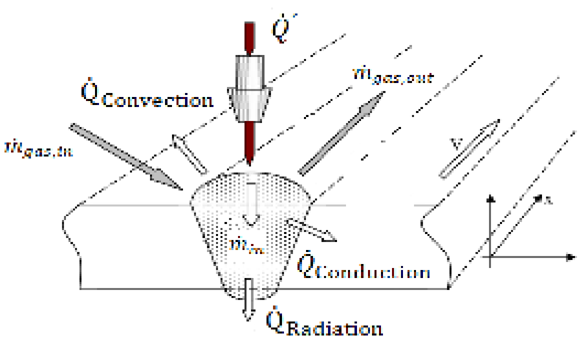

Figure 1 : heat and mass transfer flux during welding

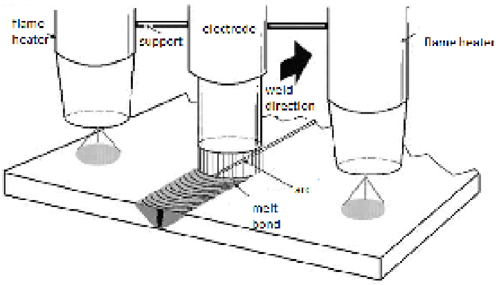

Figure 2: Parallel heating mechanism

Energy and exergy efficiencies equations for welding

Energy efficiency for welding is introduced as follow [12]:

$$\eta_I = \frac{\text{energy for welding bond generation}}{\text{total input energy}} \qquad (1)$$

This equation can be rewired as follow :

$$\eta_{II} = \frac{\dot{m}_{bond}\left(h_b - h_{in}\right)}{\dot{Q}'} \qquad (2)$$

Which $\dot{m}_{bond}$, h_b,h_{in} are the changes rate of welding bond mass , specific entropy of bond and internal specific entropy(welding bond), respectively. Evaporated metal mass can be ignored [13]:

$$\eta_I = \frac{\dot{m}_{bond}\left[C_{p(solid)}\left(T_m - T_{Pr}\right) + L_m\right]}{\dot{Q}_{Conduction} + \dot{Q}_{Convection} + \dot{Q}_{Radiation} + \dot{m}_{Gas,out}\, h_{Gas,out}} \qquad (3)$$

$$= \frac{\dot{m}_{bond}\left[C_{p(solid)}\left(T_m - T_{Pr}\right) + L_m\right]}{UI}$$

Which $C_{p(solid)}$, $L_{m,}$, T_m and T_{Pr} are specific heat capacity for bond metal, latent heat of melting, temperature of the weld metal bond and initial temperature of piece, respectively. Dividing the numerator and denominator of the ratio to welding speed:

$$\eta_I = \frac{v.m_{bond}\left[C_{p(solid)}\left(T_m - T_{Pr}\right) + L_m\right]}{UI.d} \qquad (4)$$

Which d and v are the length of weld bond and the speed of weld flame, respectively. Exergy efficiency for welding process is follows [12]:

$$\eta_{II} = \frac{\text{exergy for welding bond generation}}{\text{total input exergy}} = \frac{\dot{m}_{bond}\left(x_b - x_{in}\right)}{\dot{X}_{Total}} \qquad (5)$$

Whichx_b,x_{in} and $\dot{X}_{Total}$ are specific exergy of welding bond, internal specific exergy (welding bond) and total internal exergy rate, respectively. It should be noticed that the rate of total input exergy is the electrical energy consumed in electrode (U.I). In the next stage of process of welding the electrical energy is appeared as heat. So, it can be amused that these energies have the same amount. As follow:

$$\dot{X}_b - \dot{X}_{in} = \dot{m}_{bond}\left[\left(h_b - h_{in}\right) - T_0\left(s_b - s_{in}\right)\right] \qquad (6)$$

Which s_b and $s_{in}$are specific entropy of welding bond and internal specific entropy, respectively. So, we can write:

$$\dot{X}_b - \dot{X}_{in} = \dot{m}_{bond}\begin{bmatrix} C_{p(solid)}\left(T_m - T_{Pr}\right) + L_m \\ -T_0\left[C_{p(solid)}\ln\left(\frac{T_m}{T_{Pr}}\right) + \frac{L_m}{T_m}\right] \end{bmatrix} \qquad (7)$$

$$\dot{X}_{Total} = \dot{Q}' \qquad (8)$$

$$\eta_{II} = \frac{\dot{m}_{bond}\left(C_{p(solid)}\left(T_m - T_{\Pr}\right) + L_m\right)}{\dot{Q}_{Conduction} + \dot{Q}_{Convection} +} \frac{+\dot{m}_{bond}\left(-T_0\left[C_{p(solid)}\ln\left(\frac{T_m}{T_{\Pr}}\right) + \frac{L_m}{T_m}\right]\right)}{\dot{Q}_{Radiation} + \dot{m}_{Gas,out}\, h_{Gas,out}} \tag{9}$$

Or:

$$\eta_{II} = \frac{v.m_{bond}\left(C_{p(solid)}\left(T_m - T_{\Pr}\right) + L_m\right)}{UI.d} - \frac{v.m_{bond}\left(T_0\left[C_{p(solid)}\ln\left(\frac{T_m}{T_{\Pr}}\right) + \frac{L_m}{T_m}\right]\right)}{UI.d} \tag{10}$$

Combination of Eq. 4 and Eq.10, energy efficiency and exergy efficiency difference or dimensionless entropy generation parameter is made up:

$$\eta_I - \eta_{II} = \frac{\dot{m}_{bond}\left(T_0\left[C_{p(solid)}\ln\left(\frac{T_m}{T_{\Pr}}\right) + \frac{L_m}{T_m}\right]\right)}{UI} \tag{11}$$

Or:

$$\eta_I - \eta_{II} = \frac{v.m_{bond}\left(T_0\left[C_{p(solid)}\ln\left(\frac{T_m}{T_{\Pr}}\right) + \frac{L_m}{T_m}\right]\right)}{UI.d} \tag{12}$$

The difference shows dimensionless entropy generation in welding .The amount of UI in welding process remains constant. So, the effective and variable parameters in entropy generation are placed in the numerator of Eq. 12. Another parameter which should be introduced and interpreted is the ratio of exergy and energy efficiencies. It will be from combination of Eq. 10 and Eq. 4 as follow:

$$\frac{\eta_{II}}{\eta_I} = 1 - \frac{T_0\left[C_{p(solid)}\ln\left(\frac{T_m}{T_{\Pr}}\right) + \frac{L_m}{T_m}\right]}{C_{p(solid)}\left(T_m - T_{\Pr}\right) + L_m} \tag{13}$$

Numerator of second phrase in the right hand of Eq. 13 shows entropy generation. Also, denominator of it is directly related to energy efficiency. The Eq.13 shows that both numerator and denominator of the discussion phrase have the inverse relation with initial temperature (T_p). In the other word, they have the same treat in the temperature change. However we tend to increase the numerator (which shows the entropy generation and it has the inverse relation with welding quality) and increase the denominator (which is proportional with energy efficiency), this is not possible because of the same treat between the numerator and denominator to the initial thermal changes. Optimal process occurs when numerator of discussed expression is decreased more than denominator. It means that the curve slope of Eq. 13 is ascended proportional to T_{pr}. If the curve slope is decreasing, it shows that the percent of decreasing the energy efficiency will be more than the percent of increasing the exergy efficiency (increasing the weld quality). This is not affordable. If the curve slope approaches zero, the percent of increasing the exergy efficiency and the percent of energy efficiency will be same.

Effects of parallel flame heating

The effects of parallel flame heating are in the amount of T_{pr}. Differential equation of heat conduction is:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{14}$$

Which α is thermal diffusivity and T is temperature distribution. Here, the following equation is satisfied by the above equation [14]:

$$T = \frac{Q}{8\left(\pi\alpha t\right)^{\frac{3}{2}}} e^{-\left\{\left(x - x'\right)^2 + \left(y - y'\right)^2 + \left(z - z'\right)^2\right\} / 4\alpha t} \tag{15}$$

Which $\acute{x}$, $\acute{y}$ and $\acute{z}$ are the coordinate of the heat source. Figure 3 is a schematic of moving heat source.

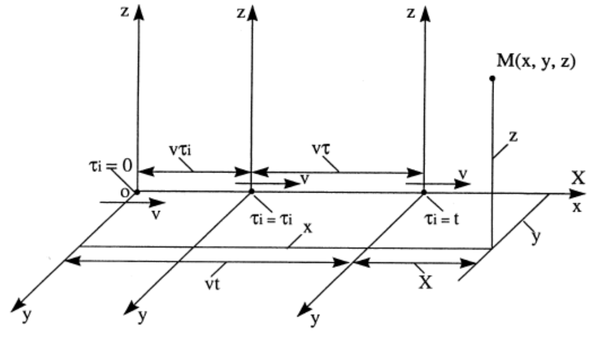

Figure 3: The coordinates of the moving heat source

x,y and z shows absolute coordinates. X, y and z are moving coordinate in direction of X axis. The distance between heating source and M is:

$$\sqrt{\left(x - v\tau_i\right)^2 + y^2 + z^2} \tag{16}$$

In this case, increasing the temperature of $d\theta_M$ in M at t because of released heat at τ_i will be:

$$dT = \frac{q_{pt}\, d\tau_i}{8\rho c\left(\pi k\tau\right)^{\frac{3}{2}}} e^{-\left\{\left(x - v\tau_i\right)^2 + y^2 + z^2\right\} / 4\alpha\tau_i} \tag{17}$$

$x - v\tau$ is the location of M in the moving coordinate. So:

$$x - v\tau_i = X + v\tau, \tau = t - \tau_i \tag{18}$$

Or:

$$T = \frac{q_{pt}}{c\rho\left(4\pi k\right)^{3/2}} \exp\left(\frac{-Xv}{2\alpha}\right) * \int_{\tau=0}^{t} \frac{d\tau}{\tau^{3/2}} \exp\left[-\frac{X^2+y^2+z^2}{4\alpha\tau}\right] \exp\left[-\frac{v^2\tau}{4\alpha}\right] \tag{19}$$

Integral section of previous equation can be expressed as a dimensionless form. For this issue the following formula is used:

$$\omega = \frac{v^2\tau}{4\alpha} \tag{20}$$

Here, Eq. 19 will be changes as follow:

$$T = \frac{q_{pt} \cdot v}{16\lambda\alpha\pi^{3/2}} \exp\left(-\frac{Xv}{2\alpha}\right) * \int_{0}^{\frac{v^2 t}{4\alpha}} \frac{d\omega}{\omega^{3/2}} \exp\left[-\omega - \left(\frac{u^2}{4\omega}\right)\right] \tag{21}$$

Which in it:

$$u = \frac{Rv}{2\alpha}$$

(22)

$$R = X^2 + y^2 + z^2 \tag{23}$$

Eq. 21 can be used in transient conditions. Integral part of this equation is solvable via numerical where had used the Simpson method to solve it. Experiments show that if welding takes enough times, such condition is created in piece which is called quasi-steady. It means that if the observer is placed on the heat source, he will not feel the differences in the temperature distribution around the heat source. In other words, if temperature distribution around the heat source is considered as the lump, it will move on piece surface like a rigid body without any changes in size and form in the quasi-steady heat transfer. It can be seen from Figure 4, as well.

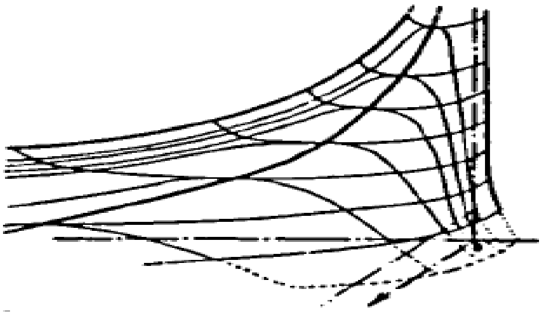

Figure 4: Isothermal lines around a point source in quasi-steady [15]

Finally, the trace of isothermal lines on piece surface would be parallel lines and in the direction of weld move. Integral of Eq. 21 will be had approximately the same amount for ω >5 (even if ω → ∞). In this case, it can be assumed the quasi-steady situation for ω>5 (because the expressions of time are in the integral and in this condition the amount of integral is constant).

Results and discussion

All studies were done on A36 steel for welding with 210A and 25v. For welding bond of this steel, assuming the combination of half of steel and electrode, latent heat of melting, melting temperature, density and average specific heat in the temperature range used are 274000 j/kg, 1482°C, 7850 kg/m^3, 310 J/kg.K, respectively.

Figure 5 illustrate the variation of energy efficiency with the rate of flames heat. It is clear that energy efficiency decreases by increasing the flames heat. Decreasing slope of this efficiency has a great amount for higher speeds. In addition, with increasing the speed the efficiency rises up.

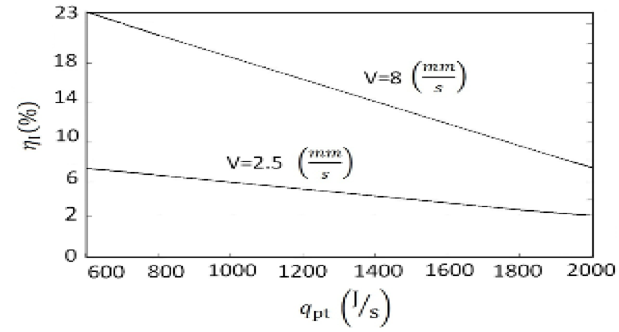

Figure 5: The variation of energy efficiency with flames heat, welding speeds 2.5 and 8 mm/s

Figure 6 illustrate the variation of exergy efficiency with flames heat. It is appear that exergy efficiency reduce by increasing flames heat. Decreasing slope of this efficiency for higher speeds has a great amount. Also, efficiency increases by rising up speed. It should be noticed that exergy efficiency is less than energy efficiency which is because of entropy generation in specific speed of welding.

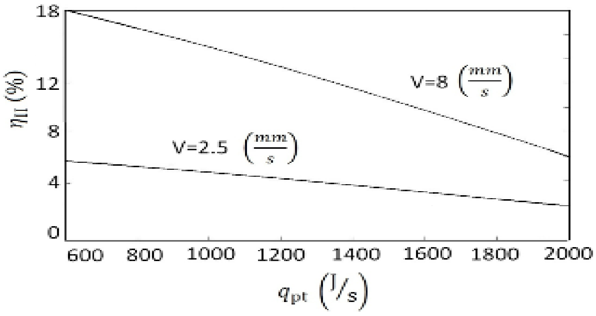

Figure 6: The variation of exergy efficiency with flames heat, welding speeds 2.5 and 8 mm/s

Figure 7 shows the variation of difference between energy and exergy efficiency (or irreversibility entropy generation) with flames heat, in 2.5 and 8 mm/s speed of welding. This difference is due to generate irreversibility during welding. In fact, it shows the amount of welding residual stresses. Results show that the residual stresses generated in piece decrease with increasing the flames heat. In addition, this Figure illustrates that the decreasing slope of dimensionless entropy decreases by increasing the flames heat. In the other word, at higher temperature, the effect of flames heat for reducing residual stresses would be decreased. Considering to Figure 7 , the effect of parallel heating for decreasing residual stresses in higher speeds are more.

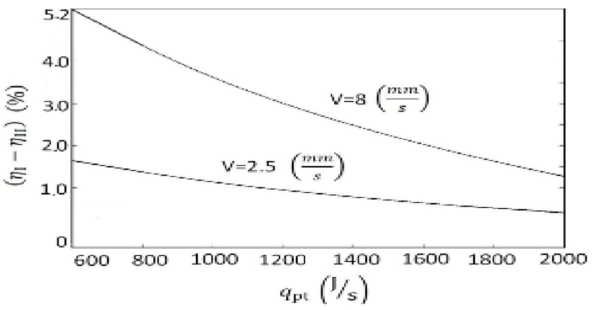

Figure 7: The variation of the entropy generation with flames heat, welding speeds 2.5 and 8 mm/s

Figure 8 indicates the experimental results of residual stresses reduction for welding bond to parallel flames heat rate changes [16]. According to the graph, however increasing the flames heat is caused to reduce the residual stresses, the rate of this reduction have descending trend. Also, at higher heating rates, the slope is closed to zero. It confirms the data's of Figure 7.

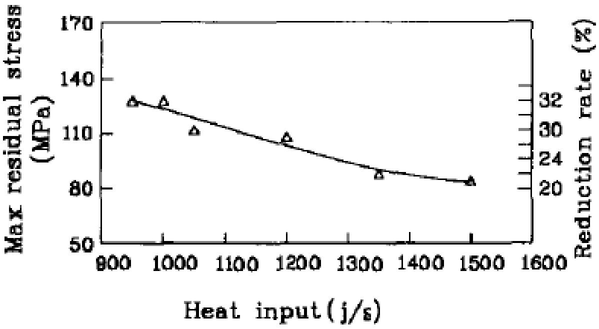

Figure 8: The variation of the maximum residual stress and reduction stresses rate with flames heat [16]

Figure 9 shows the variation of the ratio of exergy and energy efficiencies with flames heat. As it mentioned before about physical meaning of this parameter, reduction the entropy generation (increasing the welding quality) is more than the decreasing the energy efficiency where the increasing slope is faster. So, in that range increasing the flames heat can be economic. According to the Figure 9, these ranges can be considered about 1800j/s. The curve slope is near zero in heating about 1800 j/s. It shows the same decreasing rate in entropy generation and energy efficiency. However in this range, welding quality increases by using parallel heating, but energy efficiency decreases in the same rate. The curve slope decreases for heating over 1800j/s. It means that welding quality increase (residual stresses decrease) while; the energy efficiency decrease so much and this case is not optimum. The significant note is that the ratio of two efficiencies is independent to welding process speed.

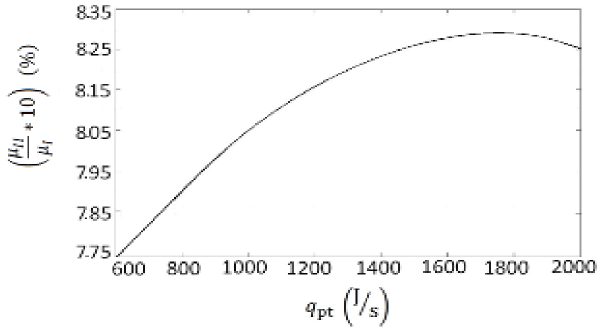

Figure 9: The variation of the exergy and energy efficiency ratio with flames heat, welding speeds 2.5 and 8 mm/s.

Conclusion

The results indicate that although increasing the flames heat is caused to reduce the energy efficiency, it increases the exergy efficiency. In heating about 1800 j/s the positive slope approach to zero. Energy and exergy efficiencies increase by rising up welding speed. The difference between efficiencies (energy and exergy) which is showed welding irreversibility or welding residual stress, increase by reducing the temperature. In the other hand, welding residual stresses decrease by increasing the flames heat. These stresses (or the efficiency differences) increase by rising up speed. What’s more, the ratio of exergy efficiency to energy efficiency which is the ratio of reduction of entropy generation to reduction of energy efficiency has a positive slope, up to heating approximately 1800 j/s. It illustrates that the reduction of entropy generation is more than reduction of energy efficiency. Therefore, up to range of this point, increasing the heat can be economic. Also, for heating more than it, the optimal cost of increasing heat is dependent on the type of welding performance. The economics of increasing the heat is not dependent on the speed of welding process. Also, adopting our results and results presented by Moslem [16] and considering to the ease usage of our method show that the differences between energy and exergy efficiency or dimensionless entropy generation can be suitable criteria from welding residual stress.

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