Energy Balance: Performing Energy Usefulness in AISI 304 Welding

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Abstract. Many researches on welding efficiencies have already been conducted, but very few of them take attention on energy usefulness in workpiece welding zone. Energy usefulness profile can be used as a reference in developing a thermodynamics model to predict post welding material properties and material behavior. The aim of this study is to obtain energy usefulness in AISI 304 welding. The study utilizes finding from previous researches to analyze and calculate the amount of energy received by a workpiece and the energy which distributed to fusion zone, high temperature heat affected zone, low temperature heat affected zone and unaffected base metal. Metal casting theory approach is required to identify useful work process in welding. AISI 304 post welding energy usefulness profiles are then performed in an energy balance diagram. The result of this study shows that energy usefulness decreases when the zone distance from the center of welding increase. The finding has a good agreement with entropy state function theory.

1. Introduction
Welding is the most common method to joint materials in product manufacturing. However, welding cost is relatively expensive due to inefficiency in energy usage. Efficiency in welding consists of process efficiency (f1) and melting efficiency (f2) [1,2,3]. Process efficiency may be defined as a ratio of heat energy received by a workpiece to the total energy generated by the source, and melting efficiency is defined as the ratio of energy used by melting process to the total energy received by the work-piece. Previous researches found that process efficiency of Gas Tungsten Arc Welding is being in the range of 0.6 to 0.8, and melting efficiency is being in the range of 0.2 to 0.4 [1,2,4,5,6]. Low value of melting efficiency indicates that most of welding energy received by base plate is excessively wasted to surrounding. Base on the thermodynamics framework the energy is not actually wasted but some is consumed by useful work and the other give rises to molecule vibration in welding zones or leave the workpiece by convection.

On the other hand, some studies were held to observed the influence of welding energy to post welding material properties and behavior [5,7-12]. The previous researches on several Aluminum alloys detected cell spacing which is expected to increase with the increase of heat energy [7,8]. Equiaxed grains in commercial aluminum alloys were observed to enhance at higher heat input [9-12].
Other previous researches successfully found that the higher welding energy the lower notch toughness values [5]. Despite the previous study has already discovered the relation between energy with material properties and material behavior, they cannot predict the values without experimental laboratory testing. The understanding of energy usefulness in welding zone can be used as reference in developing thermodynamic instrument to predict material properties and behavior which is associated with material ability to absorb energy such as toughness and fracture resistance. Therefore, energy usefulness profile is quite important as an early step in developing the post welding material properties and the material behavior prediction model. By energy balance model, this study is intended to perform post welding AISI 304 energy usefulness in each welding zone.

2. Method
AISI 304 1000 strip plate with the dimensions of mm x 100 mm x 10 mm was used as a basic material. Composition of the basic material is contained of: 0.041% C, 18.4% Cr, 0.19% Mn, 0.19% Mo, 8.5% Ni, 0.031% P, 0.54% Si, 0.014% S, 0.025% O and 0.062% N. In this study, the energy balance in AISI 304 post welding was obtained by performing energy usefulness with the following technique and procedure. Welding energy input is estimated by:

\[ H = \frac{V \cdot I}{S} \]  

where: \( H \) is Welding energy input per cm welding length (Joules/cm), \( V \) is voltage (volts), \( I \) is current intensity (amperes), \( S \) is welding speed (cm/minutes). After considering arc and melting efficiency, the welding energy was distributed to welding zone assumed as Gaussian distribution. The amount of energy per volume in each zone is as follows [13,15]:

\[ q = \frac{Q}{\pi r'^2} e^{\left(-\frac{r^2}{2r'^2}\right)} \]  

where \( q(r) \) is the amount of energy per volume in a distance \( r \) from the center of the heat source (Joules/cm\(^3\)), \( Q \) is welding energy input ; \( Q = H \cdot \) Length of welding in cm (Joules), \( r' \): Gaussian distribution parameter and \( r \) is distance from the center of the heat source (cm). Compared with the concentrated heat source based model [13,14], Gaussian distribution approach which is built with the concept of a distributed heat source provides more accurate results in prediction of heat distribution during the welding process [13,15]. The welding energy which flows through each zone is then transformed into certain useful work. Energy balance model was developed by considering welding input energy and the energy transformed into certain useful work in each zone.

2.1. Welding Zone and Energy Utilization for Useful work
Based on temperature, the welding zone is divided into: Fusion Zone, Heat Affected Zone which consist of: High Temperature Heat Affected Zone (HTHAZ) and Low Temperature Heat Affected Zone (LTHAZ) also Unaffected Base Metal Zone [11]. In Fusion zone, welding can be treated as mini casting [3,16,17,18,19,20]. The welding energy which flows through the zone is utilized for re-melting process. The quantity of energy required to melt a given weight of metal in Fusion Zone was estimated by [3]:

\[ E_m = \Delta H_{T_f} + \int_{T_1}^{T_2} C_p dT \]  

Where \( E_m \) is energy required to re-melt 1 gram of metal (Joules/gram), \( \Delta H_{T_f} \) is enthalpy at \( T_1 \) (calories/mole), \( C_p \) is molar specific heat (calories/mole.Kelvin), \( T_1 \) is temperature at known enthalpy quantities (Kelvin), \( T_2 \) is effective metal molten temperature (Kelvin) Note : For Fe, mole weight = 55.85 g and 1 calorie = 4.186 joules. In High Temperature Heat Affected Zone, despite peak of temperature below the melting temperature, the temperature is high enough for extensive grain growth. The welding energy utilized for grain growth process per unit volume was expressed as [21]:

\[ \frac{3\nu_p}{D} \]  

Where \( y \) is boundary energy per unit area (joule/cm\(^2\)), \( D \) is grain diameter (cm). When the heat is not sufficient, the grain growth no longer occurs in Low Temperature Heat Affected Zone. Recrystallization occurs in this zone during the welding process when the temperature is not
enough to meet the needs of the Austenite formation. By assuming homogenous nucleation, energy for recrystallization in the Low Temperature Heat Affected Zone is [21]:

$$\Delta G = \frac{4}{3} \pi r^3 \Delta G_v + 4 \pi r^2 \gamma$$  \hspace{1cm} (5)

Where $\Delta G$ is total free energy (Joules), $\Delta G_v$ is free energy volume (Joules/cm$^3$), $r$ is nucleus radius (cm), $\gamma$ is surface energy (Joules/cm$^2$). Microstructure in the unaffected base metal zone was not changed, but a very high shrinkage of the fusion zone generates residual stress in the heat affected zone [16,17,18,19]. The zone residual stress evocation utilize the welding energy as follows [19]:

$$U_{rs} = \frac{\sigma_{rs}^2}{2E}$$  \hspace{1cm} (6)

Where $U_{rs}$ is energy consumed in residual stress evocation (Pa), $\sigma_{rs}$ is residual stress (Pa), $E$ is elasticity modulus (Pa). Refering to eq.(7) [23], the distribution of residual stress in AISI 304 welding is estimated by

$$\sigma(y) = \sigma_{rs\max} \left[ 1 - \left( \frac{y}{b} \right)^2 \right] \exp \left[ -\frac{1}{2} \left( \frac{y}{b} \right)^2 \right]$$  \hspace{1cm} (7)

In HTHAZ and LTHAZ sensitization process (Chromium carbide forming) also take place which consume about -10.98 kJoule atom$^{-1}$mol$^{-1}$ until -8.75 kJoule atom$^{-1}$mol$^{-1}$ [24,25,26,27,28,29]. Base on the residual stress distribution, it is necessary to consider the residual stress evocation energy in both zones.

2.2 Model Formulation

Based on The first law of Thermodynamics that heat and work have the same influence on increasing the internal energy of body. They have the same units and can be converted from one to another [30]. Welding process can be consider as heat transfer process from welding machine to work piece which result in internal energy increase. On the other hand, when the same body subjected to an impact loading the strain energy will increase in the amount of potential or kinetic energy of impact mass pendulum [31,32]. Both welding and impact loading have the same effect on internal energy of the body. Base on the framework, energy balance in the welding of AISI 304 should consider the effect of welding on the ability of material in energy absorption. The concept of energy balance in each welding zone obtained by comparing pre welding ($E_{m}$) with post welding ($E_{mw}$) ability of material in energy absorption. Post welding ability of material in energy absorption is reduced by the additional amount of welding energy ($Q_{w}$) diminish by energy utilization in each zone ($W_{wo}$). The energy balance model in each zone is expressed as follows:

$$E_{m} = E_{mw} + (Q_{w} - W_{wo})$$  \hspace{1cm} (8)

Where $E_{m}$ is Initial impact energy (pre-welding impact energy, Joules/cm$^3$ zone volume), $E_{mw}$ is Post welding impact energy (Joules/cm$^3$ zone volume), $Q_{w}$ is Welding energy (Joules/cm$^3$ zone volume), $W_{wo}$ is Energy utilization in each zone (Joules/cm$^3$ zone volume). Welding energy $Q_{w}$ estimated by eq.(1) and distributed to each zone follows the Gaussian distribution by eq.(2). Energy utilization in each zone is estimated by eq (3),(4),(5),(6). The energy balance model in the each zone is then:

- **Fusion Zone**
  $$E_{m} = E_{mw} + (Q_{w}) - W_{wo}$$  \hspace{1cm} (9)

- **Heat Affected Zone**
  - **High Temperature Heat Affected Zone (HTHAZ)**
    $$E_{m} = E_{mw} + (Q_{w}) - W_{wo}$$  \hspace{1cm} (10)
  - **Low Temperature Heat Affected Zone (LTHAZ)**
    $$E_{m} = E_{mw} + (Q_{w}) - W_{wo}$$  \hspace{1cm} (11)
The energy balance model has been applied on AISI 304 welding by four layer DC current Tungsten Gas Arc Welding with 1.6 mm ER 308 L filler metal in each layer and 12 L/min gas flow. Welding zones were determined by microstructure characteristsi/Fusion zone is located in the range of 0 – 3.65 mm from the center of welding bead. Sensitization which indicated by chromium carbide precipitation in grain boundary is occurred in HTHAZ in the range of 3.65 mm – 4.4 mm and in the LTHAZ in the range of 4.4 mm – 6 mm from center of welding bead.

Grain size in HTHAZ microstructure is coarse with the size of 10 micron when LTHAZ grain size is finer with the size of 3 micron and smaller. Unaffected base metal is located in the range of 6 mm – 50 mm from center of welding bead indicated by similar grain with the original base metal microstructure. Some input parameters for the similar materials or corresponding process taken from AISI 304 datasheet and refs. [2,6,15,16,33,34] such as:

- $E_m$ : 325 J , $D_{HTH}$: 17.61 kilo calories/mole weight. $T_1$: 1800 K, $T_2$: 2023 K, $C_p$: 1800 : 10.5 calories/mole weight, $\sigma_{r, max}$: 215 Mpa (as high as yield strength). $\rho$ : 8 g/cc, $\gamma$ : 1169 erg/cm$^2$, $\Delta G_v$ : -3000 J/cm$^2$, $r$ : 8 A = 8 x 10$^{11}$ Pa.

### 3. Result and Discussion

#### 3.1. Model Examination

Charpy Impact test was used to find the values of initial and post welding impact energy. Energy balance must meet the rules of thermodynamic equilibrium in each zone. The initial impact energy ($E_{mi}$) and post-weld impact test results ($E_{mw}$) become references of energy changes calculation during the welding process ($Q_{wi}$-$W_{wo}$). The result of energy balance calculation is shown in Table 1.

| Zone       | FZ          | HTHAZ  | LTHAZ  | UBM          |
|------------|-------------|--------|--------|--------------|
| Initial energy ($E_{mi}$) | 296.56    | 60.93  | 130.00 | 3575.00      |
| Welding energy ($Q_{wi}$) | 5412.53    | 279.01 | 802.00 | 15297.57     |
| Energy consumption ($W_{wo}$) | 5312.30    | 251.65 | 714.79 | 12977.47     |
| Post weld impact energy ($E_{mw}$) | 196.33    | 33.57  | 42.79  | 1254.90      |
| $E_{mi}$ - $E_{mw}$ | 100.23    | 27.36  | 87.21  | 2320.10      |

In fusion zone, thermodynamics equilibrium is fulfilled when energy change in welding process ($Q_{wi}$ – $W_{wo}$) in amount of 100.23 Joules. Considering the thermodynamic equilibrium, energy balance equation in fusion zone is then enhanced and expressed as follows:

$$E_{mi} = E_{mw} + (0.987 (Q_{wi} - W_{wo}))$$

(11)

$E_{mi} = E_{mw} + (\Delta H_{HTH} + \int_{T_1}^{T_2} C_p dT)$

(13)

Energy balance in High temperature heat affected zone is displayed on Figure 8. As previous procedure, thermodynamics equilibrium has to be fulfilled with the result that energy change in welding process ($Q_{wi}$ – $W_{wo}$) in amount of 27.36 Joules . Energy balance equation in high temperature heat affected zone then becomes:

$$E_{mi} = E_{mw} + (0.25 (Q_{wi} - W_{wo}))$$

(14)
According to thermodynamics equilibrium in Low temperature heat affected zone, energy change in welding process \((Q_{wi} - W_{wo})\) has to be in amount of 27.36 Joules.

By the same previous procedure, an enhanced energy balance equation becomes:

\[
E_{mi} = E_{mw} + \left(0.35 \, Q_{wi} - W_{wo}\right) + \left(4\pi r^2 \Delta G_v + 4\pi r^2 \gamma + 10.98 + \frac{\sigma T^2}{2E}\right)
\]

(15)

As a consequence of thermodynamic equilibrium, energy change in welding process \((Q_{wi} - W_{wo})\) in unaffected base metal zone has to be in amount of 2320.10 Joules.

Energy balance equation at UBM zones is then expressed as follows:

\[
E_{mi} = E_{mw} + \left(0.68 \, Q_{wi} - W_{wo}\right)
\]

(16)

The percentage of energy consumption to welding energy absorption in all zones is at the level more than 80%. These facts show that most of the energy absorbed in all zones is consumed by the useful work which occurs by unique way in each zone. The percentage of energy consumption to the welding energy absorption in each zone varies with the highest percentage occurred in the fusion zone and decreases away from the center of welding as shown in Table 4. This fact shows the high energy usefulness in fusion zone and decrease in HTHAZ, LTHAZ, uBM respectively. It can be explained by entropy state function expressed as bellow [35]:

\[
\delta S = \frac{\delta Q}{T}
\]

(17)

Where \(\delta S\) is entropy changes, \(\delta Q\) is the amount of heat absorbed by the system, \(T\) is absolute temperature (K). The entropy formula above denotes the relation between entropy and energy usefulness macroscopically. Energy supplied at high temperature will be absorbed more to do useful work than the same amount of energy supplied at lower temperature [35]. That is also the reason why welding energy in unaffected base metal zone (6mm – 50 mm from center of welding) is less useful. Microscopically, the quantity of energy that can be dispersed in the molecules depend on their state [28]. In the warm solid crystals, the molecules vibrate back and forth more than in cold one. It is the rationale that warm solid absorbs more energy to do work than cold solid [36].

4. Conclusion

The study successfully reveals energy usefulness of AISI 304 post welding. By energy balance model, energy usefulness in each zone was calculated and enhanced by the result of Charpy impact test. The energy usefulness is decreased by increasing spacing away from the center of welding. The usefulness profile macroscopically corresponds to entropy state function and microscopically reasonable. Based on the energy balance model, it is recommended to continue this study to predict the values of material behavior and material properties in term of the ability in energy absorbance such as toughness and fracture resistance.

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