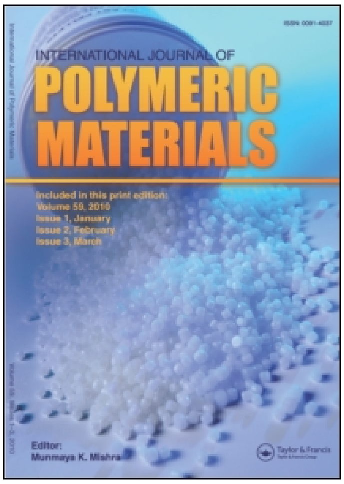

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A Mathematics Model of The Plastic Socket Welding and The Analysis of Its Welding Performance

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Through the analysis of the heat and mass transfers, the boundary condition of the temperature field in plastic sockets were determined. By the particular attention paid to the analysis of the boundary surface temperature during the heat-up period and change-over period, a set of mathematical models were developed. The mathematical model can supply theoretical basis for the improvement of the welding quality. We also used HDPE as the experimental materials to analyze the performance of the welding joint by the heat-treating method and DSC.

KEY WORDS Plastic welding, mathematical model

INTRODUCTION AND EXPERIMENTS

Socket welding is employed for melting the external surface of the pipe and the internal surface of the socket head by using the heating device, and joining plastic parts with shifting the pipe into the socket head. It is a multi-step, interactive physical process in which heat-up, change-over, and welding process are dominant,[1] and the joint of the parts is a barreled socket joint, which can be regarded as a lap joint. When the welding parts are heated, plastic in the welding seam is dense, and compressed force is functioned to internal shell. Therefore, it is possible to lose stability when the pipe is joined to socket head. On the other hand, lack of heating time also causes welding defect. Hence, control of welding temperature and heat-up time is very important.

Welding quality is also affected by change-over process. Generally, the shorter the change-over time is the better, particularly when it is not allowed to exceed 10 seconds.

Experiments were done with a commercial laboratory welding machine using tube whose internal radius was 32 mm and wall thickness was 3 mm. The materials (DGDB 2480) were from Qilu Petrochemical Co. The socket head used were bi-pass pipe, swan-neck, and T-shaped pipe whose external radius was 42 mm and wall thickness was 5.6 mm. Heat-up temperature was set to 235°C and 265°C. Heat-up time was 10 seconds. Change-over time was less than 6 seconds.

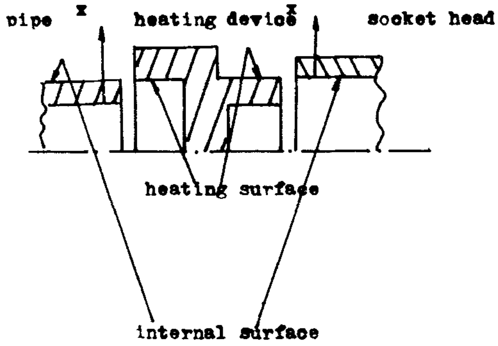

FIGURE 1 Coordinates.

RESULTS AND DISCUSSION

Temperature Development of Socket Welding

The welding seam quality depends on the viscose flow state of melted materials under pressure in welding zone. Therefore, it is very important to analyze heat-transfer during heat-up and change-over processes and establish a mathematical model to simulate the temperature field of welding zone.

Determination of heat transfer boundary conditions. Several assumptions to simplify the problem are as follows: (i) only one-dimensional radial heat conducting; (ii) no influence of non-heating region; (iii) no temperature increment with heat-up time increasing on the heated surface.

Heating process analysis of socket head. According to above assumptions, the heat transfer equation under cylindrical coordinate can be given. Considering that most of pipes' wall thickness is much smaller than their diameters, we can substitute the pipe for the limitless wide plate model to solve the equation (Figure 1). The one-dimensional heat-transfer equation is

$$\frac{\partial T}{\partial t_h} = a \frac{\partial^2 T}{\partial X^2} \, (0 < X < W, \, t_h > 0) \tag{1a}$$

$$T|_{x=0} = T_h \tag{1b}$$

$$\left(\frac{k}{h} \frac{\partial T}{\partial X} + T \right) \bigg|_{x=w} = T_c \tag{1c}$$

$$T|_{t_h=0} = T_c \tag{1d}$$

the solution is

$$\frac{T - T_c}{T_h - T_c} = 1 - \frac{X}{\left(W + \frac{k}{h} \right)} - \psi \tag{2a}$$

$$\psi = \sum_{n=0}^{\infty} \frac{2}{\lambda_n W'} e^{-\lambda_n^2 a t_n} \sin(\lambda_n x) \tag{2b}$$

$$tg(\lambda_n W) = -k\lambda_n/h \tag{2c}$$

$$W' = W - \sin(2\lambda_n W)/(2\lambda_n) \tag{2d}$$

where: a—temperature transfer coefficient, mm^2/°C; k—heat transfer coefficient, w/mk; h—heat-exchange coefficient, w/m^2 k; T—temperature, °C; W—wall thickness, mm; T_h—actual temperature of hot-plate surface, °C; T_c—environment temperature, °C; t_h—heating time, sec.

Heat-up process analysis of the internal pipe. There are similar aspects of heating coordinations between the internal pipe and the socket head. The difference between them is that the external wall of the socket head is assumed to be cooled freely, whereas the external wall of internal pipe is assumed to be heated, and its internal wall is in heat-insulating state. Such assumptions are acceptable, because the heating cannula is separated from outer environment when it heats the internal pipe. Thus, heat-transfer equation can be given as Equation (1), but Equation (1c) should be changed as follows:

$$\left.\frac{\partial T}{\partial X}\right|_{x=w} = 0 \tag{3a}$$

the solution:

$$\frac{T - T_c}{T_h - T_c} = 1 - \sum_{n=0}^{\infty} \frac{2}{\lambda_n W} e^{-\lambda_n^2 a t_h} \sin(\lambda_n X) \tag{3b}$$

$$\lambda_n = \frac{2n + 1}{2} \pi \tag{3c}$$

Change-over process analysis of socket head. Change-over process affects welding quality obviously, but it is difficult to determine the boundary conditions when the heated surface is separated from the special-shaped hot plate. In this paper, welding surface of the socket head is considered as heat-insulating. Because the air in the pipe is heated during heat-up process, it becomes possible to make the temperature between the air and pipe internal wall have little difference. Thus, this process heat-conducting equation can be given as follows:

$$\partial \frac{T}{\partial t_u} = a \frac{\partial^2 T}{\partial X^2} \, (0 < X < W, t_u > 0) \tag{4a}$$

$$\left.\frac{\partial T}{\partial X}\right|_{x=0} = 0 \tag{4b}$$

$$\left(\frac{k}{h}\frac{\partial T}{\partial X} + T\right)\Bigg|_{X=W} = T_c \tag{4c}$$

$$T|_{t_u=0} = T(X, t_h) \tag{4d}$$

where: t_u—change-over time, sec

the solution:

$$\frac{T - T_c}{T_h - T_c} = \sum_{m=0}^{\infty} A_m e^{-\beta_m^2 a t_u} \cos(\beta_m x) \tag{5a}$$

$$tg(\beta_m W) = h/(k\beta_m) \tag{5b}$$

Where A_m is relational to heating aspect.

$$A_m = \frac{2}{W + \dfrac{\sin(2\beta_m W)}{2\beta_m}}\left(\frac{1}{(W + k/h)\beta_m^2} - \phi\right) \tag{5c}$$

$$\phi = \sum_{n=0}^{\infty} \frac{2}{W'(\lambda_n^2 - \beta_m^2)} e^{\lambda_n^2 a t_h} \tag{5d}$$

Change-over process analysis of internal pipe. The outer surface of the internal pipe is exposed to air during change-over process. Assuming the internal surface of this pipe is still heat-insulating, then the temperature distribution equation can be given as in Equation (5), but Equations (5c) and (5d) must be changed as follows:

$$A_m = \frac{2}{W + \dfrac{\sin(2\beta_m W)}{2\beta_m}}\left(\frac{\sin(\beta_m W)}{\beta_m} - \phi\right) \tag{6a}$$

$$\phi = \sum_{n=0}^{\infty} \frac{2}{W(\lambda_n^2 - \beta_m^2)} e^{\lambda_n^2 a t_h} \tag{6b}$$

Analysis of the model. For an example, the wall thickness of a HDPE socket head was 5.6 mm; Figures 2–4 give the calculation results.

In Figure 2, this is obvious for the temperature variation of the welding zone during initial heating stage. According to Equation (2), when heating time is long enough, temperature almost distributes along the straight. Its limited pattern is:

$$(T - T_c)/(T_h - T_c) = 1 - X/(W + k/h) \tag{7}$$

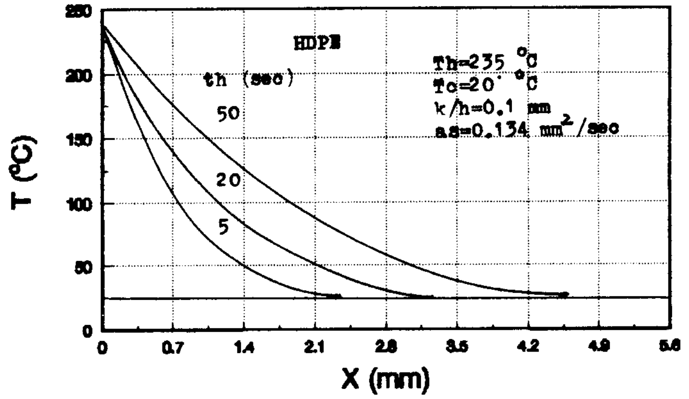

FIGURE 2 Temperature distribution of the socket head along the wall thickness at different heat-up times.

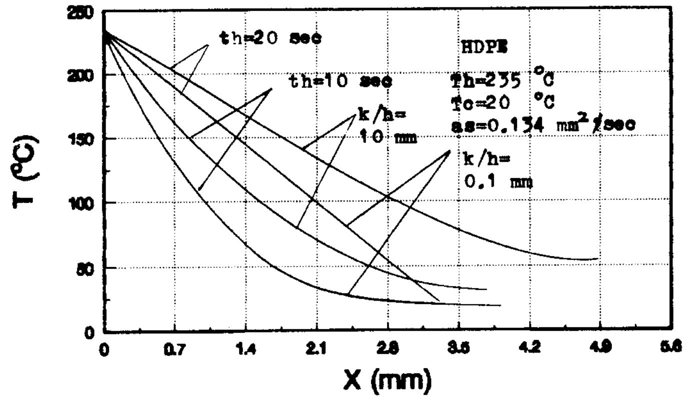

FIGURE 3 Temperature distribution of the socket head along the wall thickness under different environment condition.

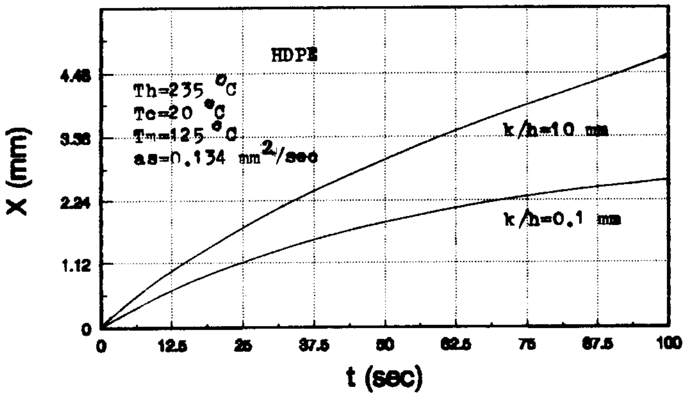

FIGURE 4 Melted zone development along the direction of wall thickness under different environment condition.

When the heating time reached a regular value, the temperature already approaches the result of Equation (7). So there is no possibility to change the temperature distribution by increasing heating time (Figure 3). When heat-up time is short, and the alteration of the ratio k/h is small, the influence to the temperature distribution is also small (especially to thick wall tube). This shows that the dependence on environment during the heat-up phase within the range of welding technology is not remarkable.

Figure 4 shows the developing trend of melted zone. if the value of k/h is already rather large, but we have not yet limited the heat-up time, it will lead to overdevelopment of melted area and make the whole socket head soften and become deformed. Thus, we have not enough rigidity to fulfill socket welding. From this aspect, it is necessary to limit heat-up time. On the other hand, when the value of k/h is rather small, the melted zone may be also small, and if we need deeper melted depth, it will be of no use to lengthen the heat-up time. The maximum possible melted depth X_m is given as follows:

$$X_m = (w + k/h)(T_h - T_m)/(T_h - T_c) \tag{8}$$

The above mentioned content referred to the approximation model of heat conduct process of the socket head and the internal pipe by simplification. Although the temperature distribution is affected during the process from initial heating to the last welding, the approximation method gives an optimizing way at least. According to the assumption of optimum melting depth, we still can determine the different suitable heating times of the socket head and the internal pipe by neglecting other factors such as radius difference, rheologic properties, welding force, and so on. In order to reduce the time, the heat-up temperature in general is set to as high as possible. But this is limited by heat resistance of the materials.

From the theoretical analysis, several results are obtained as follows:

(1) Under general condition, the parameters of socket welding with the same materials have few changes.

(2) There are upper and lower limits for heating time, so we should guarantee enough melted depth without making the weld soften.

(3) During change-over process, the temperature change of welded surface of the socket head is not as intensive as that of the internal pipe. Therefore, the largest change-over time is determined by the temperature alteration of the welded surface of the internal pipe.

(4) Allowing time of moving the socket head and the internal pipe into heating device is limited by the optimum range of heat-up time.

Socket Welding Joint Performance Analysis

Heat-treating analysis of cut sheet of joints. There is no unified technique for testing the performance of a socket welding seam. Socket welding is a crossover lap between the socket head and the internal pipe. Shear force exists when the weld is drawn, therefore, it is not ideal for testing tensile strength. So we took the measures of heat-treating the cut sheet in the welding seam,^{2} and by observing whether the welding seam formed cracks or came off, the welding quality could be evaluated (Figure 5).

In this experiment, sheets with a thickness of about 100 μm were cut, respectively, along the vertical and parallel pipes' axial direction, then heated to 180°C for 5 min. The samples welded under respect condition did not present crack in the welding zone, showing that the strength of contacting surface under such circumstance was satisfactory.

DSC Analysis. Setting the welding seam as the origin of coordinates, the distance between the samples and the welding seam as the abscissa, and the value of the melting enthalpy as ordinate to illustrate, the crystallinity distribution at both side of weld could be obtained (Figure 6).

In general, the crystallinity distribution at both side of the socket welding seam was similar to that of hot-plate welding.[3] This is relative to the fact that heat-conducting of the socket weld is mainly radial. Only due to the different heating method (heating external and internal wall) and the different change-over process (internal pipe is exposed in the air, but the internal surface of the socket head is still in contact with the hot air), are the shapes of these two curves at both side not completely alike. The crystallinity close to the welding seam is obviously higher than elsewhere, especially nearby the symmetry face. Here the curve presents the maximum. This is thought to be relative to the highest flow speed that leads to the highest crystallinity. However, there is a lower value on the symmetry face, which is due to the fact that during the change-over process, the heat convection with

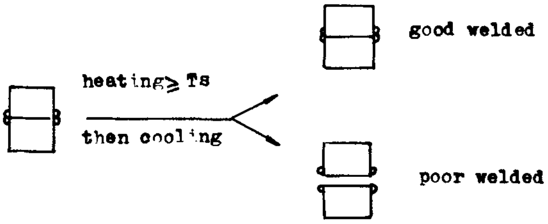

FIGURE 5 Heat-treating technique to estimate the welding quality.

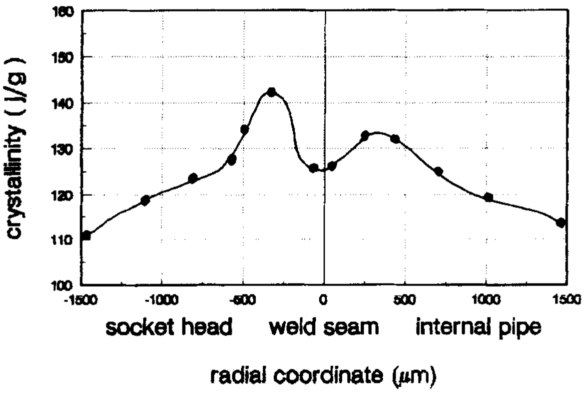

FIGURE 6 Crystallinity distribution of a socket welding joint.

the air makes surface temperature on both open surface decrease quickly, so the crystallinity in this symmetry face also decreases.

CONCLUSION

Welding property of DGDB 2480 pipe from Qilu Co. is good in the range of the DVS welding standard. The control of heat-up temperature and time is very important.

The DSC experiments show that the crystallinity distribution of the socket head and the internal pipe is different because of their different change-over processes, and all crystallinity in welding zone is higher than that elsewhere in overall trend.

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