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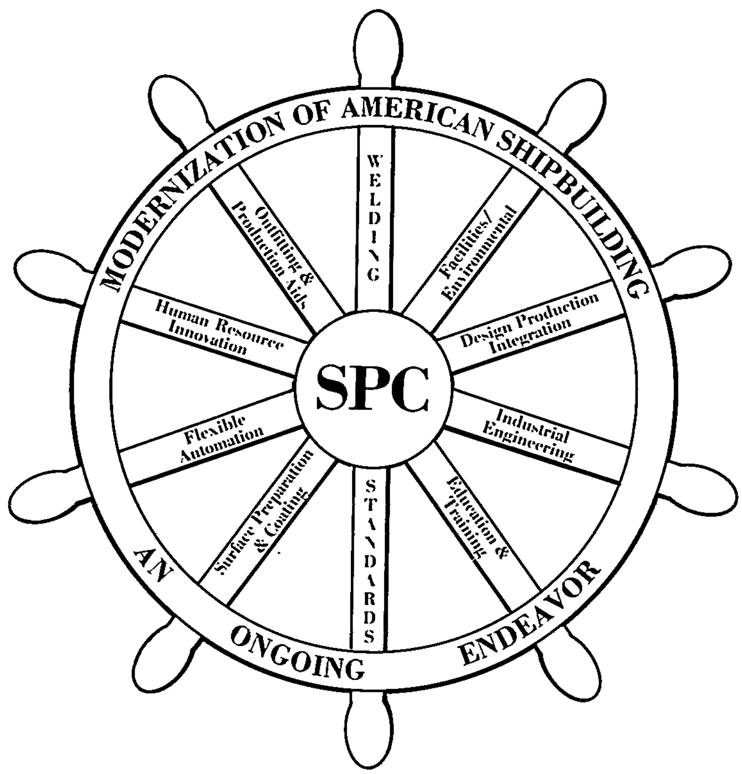

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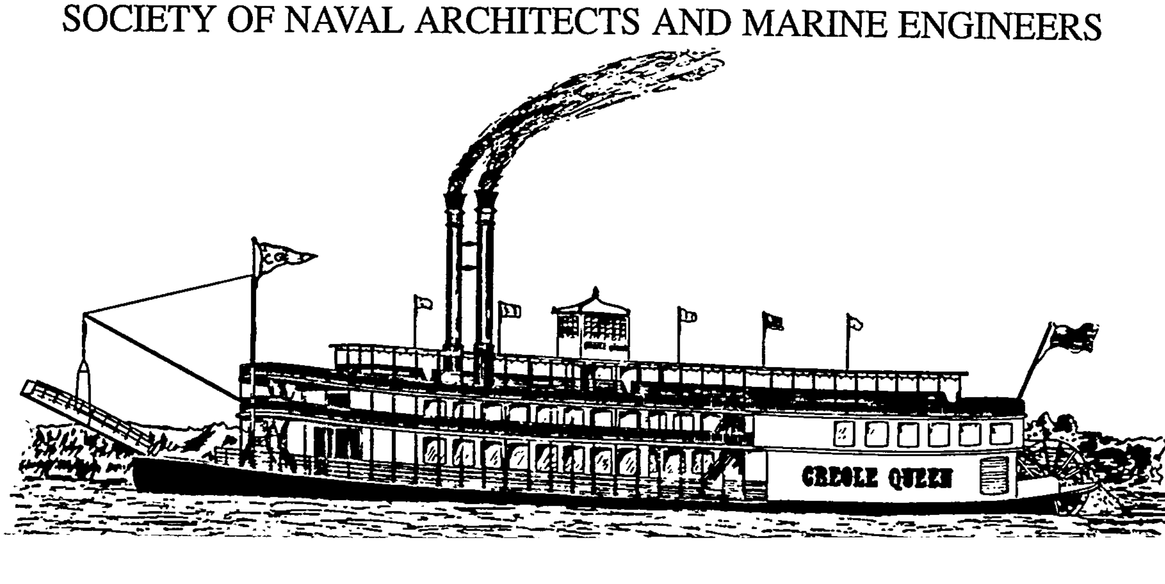

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Soviet Technique for Estimating Post-Welded Deflection: Case of Butt Welding

No. 15

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ABSTRACT

The hulls of modern ships are almost entirely welded. This makes the prediction of postwelded deformations very important. The number of parameters involved in the process of welding are large so the exact mathematical theory for prediction of deformations is unavailable. Some researchers have estimated the postwelded deflections based on empirical and semi-empirical equations. The growing literature on the study of postwelded deflections of hull plates enables the estimation of these deflections based on the plate geometry and the plate material. The limited number of critical parameters covered by these experiments makes it difficult to systematically organize the data. This has delayed the introduction of a framework for estimating the influence on the plate deflection from welding speed, current, number of passes, welding rod size and material, etc.

The approach adopted in the Soviet Union was to develop an integrated framework to include the critical welding parameters. The main Results from this approach were published in several books, with the main reference being a book by Kuzminov published in 1974.

From the standpoint of Ship Production it is useful to understand this Russian approach as well as to give examples of its use. Therefore this paper:

1. Introduces the Russian procedure for calculation of deflection due to butt welding;
2. Presents the graphical aids used in this procedure;
3. Presents a worked example using this procedure for a butt welded plate.

INTRODUCTION

With the introduction of welding to shipbuilding it became necessary to control the out of plane distortions resulting after the welded plates cooled. This postwelded behavior can have a critical influence on the strength of the steel structure. This concern has led to several approaches to dealing with this problem.

1. Postwelded plate deflection measurements of laboratory tests [1], [2].
2. Postwelded plate deflection measurements actual shipbuilding plates [2], [3], [4].
3. Development of semi-empirical formulas to estimate the postwelded plate deflection for a given welding situation [5].
4. Development of numerical codes for estimating the postwelded plate deflection [6].

Due to the large number of critical parameters such as the speed of the welding element, the plate dimensions, the plate thickness, the amount of heat transferred and the cooling process, it has been difficult to perform an analysis of the welding process which often involves large postwelded plate deflections.

This has made it difficult to introduce a methodology to account for all the critical weld parameters. Thus in the work of Antoniou et al. [3], [4] a large number of welded ship plates were studied to relate the postwelded out of plane deflection patterns to the plate geometry and thickness under the assumption that the welding process is repeatable. The interested reader can also find an extensive number of results for different weldments in the book of Professor K. Masubuchi [2].

While these works provide guidance, they are unable to completely account for the welding parameters. In contrast, the welding research in the Soviet Union has attempted to account for the welding parameters through a specially developed methodology which treats the welding process contributing to the postwelded deflection. This Soviet methodology is presented in a semi-empirical format described in the book of S. A. Kuzminov [5]. This book incorporates the results of numerous experiments and is based on the principles of heat transfer and strength of materials. In developing this method, Kuzminov made use of 109 Russian works on the subject of welding and post-weld deformations in fillet and butt welded steel structures. The comprehensiveness of this method can be understood from Table 1 which summarizes the input parameters used to estimate the post-welded plate deflections resulting from butt welding of two plates.

Using the input data in Table I a number of graphs and semi-empirical formulas are employed to calculate the following:

a) Longitudinal shortening of the welded structure. If it exceeds a critical value, the structure becomes unstable and this results in additional out-of-plane deflections.
b) Heat energy of weld per unit length. This energy depends on the number of passes, flux presence, etc. This heat energy and additional parameters are used to find the angular deformation of the butt welded structure after each weld pass.
c) The total angular deformation and normal deflection. These are obtained as the sum of angular deformation resulting from each pass. If the welded plates are found to be unstable the corresponding deformations are also added.

In this paper we present the outline of Kuzminov's method applied to postwelded deformations of butt welded plates. A numerical example is given to illustrate the application of his methodology.

The utilityof this paper is that it enables the reader to come to an understanding of the relationship of the welding process with the final deflections, as well as to provide the reader with a framework for conducting future research on the determination of postwelded deflections.

ANALYSIS

Figure 1 shows the cross section of a plate of thickness t_p made up by butt welding flat sections of width b. The postwelded deformation is due to the angular deformation denoted as β taken at plate butt welded edges. Fig. 1 shows typical section which is not influenced by the presence of side structure.

The maximum out-of-plane deflection of the plate mid-span is given by:

$$f_\beta = \frac{\beta b}{8} \qquad (1)$$

In some cases the plate edges are restrained as shown in Fig. 2. In such a situation the maximum plate deflection is given by:

$$f_\beta = 0.037 \ \beta a \qquad (2)$$

where a is the distance between the restricted edges.

The plate can become unstable from the longitudinal shortening at the welds occurring after the edge restrictions are removed. The condition of instability is given by

$$\frac{v}{b\, t_p} > \varepsilon_{cr} \qquad (3)$$

Table 1. Summary of Input Data Used in Estimating Post Welded Plate Deflection Caused by Butt Welding [5]

Input Data

a) Geometry of Plates (length, width, and thickness)

b) Material Data:

- Coefficient of linear expansion
- Density
- Specific heat capacity
- Strain at yield point
- Modulus of elasticity
- Poisson's ratio
- Thermal conductivity
- Melting point
- Yield temperature
- Strain corresponding to the yield limit

c) Welding Data:

- Electrode diameter
- Weld velocity
- Current and voltage

where

v = the volume of longitudinal shortening of the butt weld per unit length (cm^3/cm)

b = width of the butt welded plate sections (cm)

E_{cr} critical value of deformation.

The critical value of deformation E_{cr} can be approximately determined using:

$$E_{cr} = 0.9 \frac{t_p}{\ell} \left(1 + 0.448 \frac{f_\beta^2}{t_p^2}\right) \qquad (4)$$

ℓ being the length of the plate.

The volume of longitudinal shortening per unit length is given by

$$v = K_m V_m \qquad (5)$$

where Km is a coefficient given by

$$K_m = 1 + \frac{\varepsilon_s m}{8 \gamma \frac{o}{\epsilon_y} \theta} \qquad (6)$$

where m is the number of passes,

ε_s is the strain corresponding to the yield limit of the material,

γ is the density of the material, g/cm^3

c is the specific heat capacity of plate, cal/g x °C

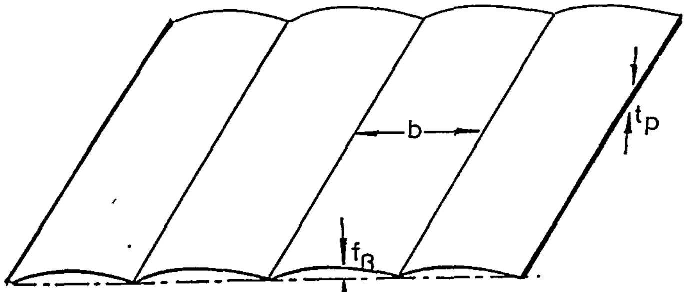

Fig. 1. Geometry of Butt Welded Plates without Constrained Edges [5]

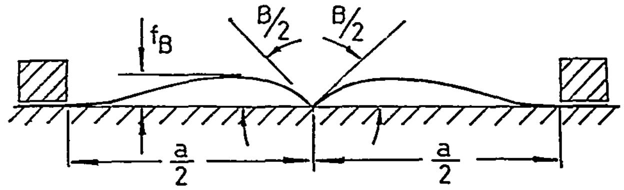

Fig. 2. Geometry of Butt Welded Plates with Constrained Edges [5]

a_o $\frac{\lambda}{Cy}$ is the rate of heat transfer in the plate, cm^2/sec.

A is the thermal conductivity, cal/cm x sec x ^0C

θ is the coefficient of proportionality between the heat energy per unit length and the cross sectional area of the weld, cal/cm^3

V_m is the volume of shortening due to one pass

If the number of passes are equal to 3 or less $K_m \approx 1$ and

$$v = V_m \sim 0.29 \frac{\alpha}{c\gamma} q_P$$

For mild steel plates

$$v \simeq V_m \simeq 3.6 \times 10^{-6} q_p \qquad (8)$$

If the inequality (3) is satisfied, i.e., the plate becomes unstable the deformation f can be calculated as:

$$f = 0.6\, \ell \sqrt{\frac{\cdot}{h\, t_p}} - \varepsilon_{cr} \qquad (9)$$

The heat energy per unit length of butt welded plate is estimated from:

$$q_p = 0.24 \frac{IU}{V} \eta \quad \text{(cal/cm)} \qquad (10)$$

where
- 1 = welding current (amps)
- U = voltage of arc (volts)
- V = speed of welding (cm/sec)
- n = effective efficiency based on welding material.

Typically $0.65 \leq \eta < 0.80$.

If welding is performed under flux a part of the heat energy is absorbed by the heating and melting of the flux. This lost heat energy q_{nf} can be estimated based on the heat energy given by (10):

$$q_{nf} = \eta_f\, q_p \qquad (11)$$

The coefficient K_f is given in Fig. 3 as a function of electrode diameter d . Measurements have indicated that K_f falls between curves 1, 2 in Fig. 3. The dashed line in Fig. 3 can be used to give representative K_f values when performing calculations.

The angular deformation B due to multi-pass butt welding can be found as

$$\beta = \sum_{i=1} (\pm\, \beta_i) \qquad (12)$$

where m is the number of passes and β_i can be determined using Fig. 4.

The sign "+" in (12) corresponds to the case when the angle between the welded plates measured from the upper surface decreases when the weld pass is completed. The sign "-" corresponds to the case when the angle increases.

The parameter S in Fig. 4 is calculated by

$$S = s\psi_o \eta_o \frac{q'_p}{t^2_{i=1}} \quad (cal/cm^3) \qquad (13)$$

where
- q'_p = effective heat energy per unit length, cal/cm.
- ψ_o = relative heating coefficient
- n_o = heat transfer efficiency
- t_i = height of the cross section of the-butt weld after the i-th pass (cm) as shown in Fig. 5.

It is necessary to determine the value of S from the welding processes. For arc welding the welding electrode diameter d_e, the separation gap between the plate and the electrode, and the current I are critical parameters. Fig. 6A shows the zones affected by the welding. To characterize the extent of influence the width b. and depth ho are introduced to define the relative heating coefficient ψ_o.

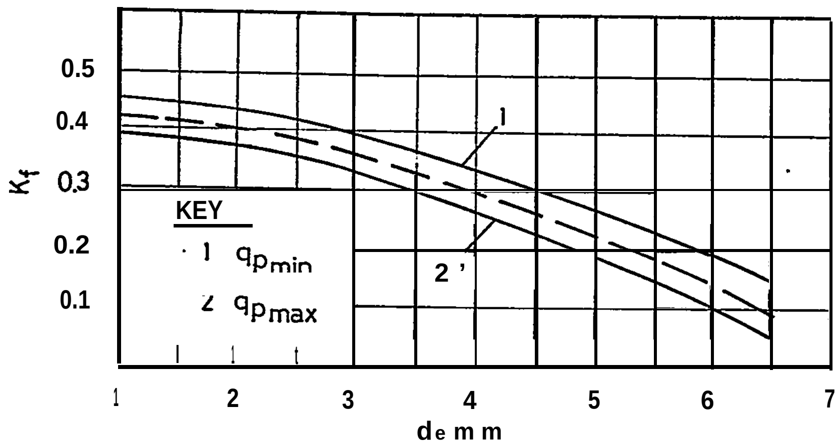

Fig. 3. Coefficient of Flux Heat Energy K_f versus Welding Electrode Diameter d_e [5].

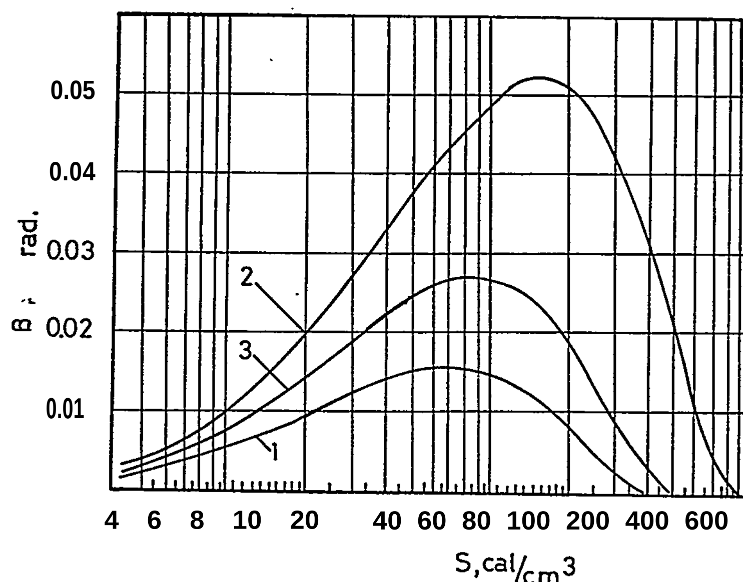

Fig. 4. Post Welded Plate Deflection Angle ß versus Heating Intensity Parameter S [5].
1: Welding with restrained edges; 2: welding with unrestrained edges, 3: multipass welding

$$\psi_- = h_o/b_0 \qquad (14)$$

A number of tests with hull plates showed that the ratio of ho/ho is within the following limits

$$1.1\ h/b < h_-/b_- < 1.2\ h/b \qquad (15)$$

Fig. 6 B presents the results from a number of tests where the current and electrode diameter were varied and the value of ψ_- was measured.

Further studies showed that the heat transmission during welding could be characterized by the parameter ε.

$$E = \frac{q'_- V^2}{c\gamma T_- a_-^2} = \frac{q'_- V^2}{\lambda T_- a_-} \qquad (16)$$

where V is the velocity of welding electrode, cm/se

T_o is the yield temperature of plate, °C

The value of q'_p has a complex relationship with the welding regime and geometry of the welded plate. To express this relationship the following formulas were introduced to cover typical welding practice:

a) One or two passes; manual welding

$$q\ {}^2{}_p\ {}^q P \qquad (17)$$

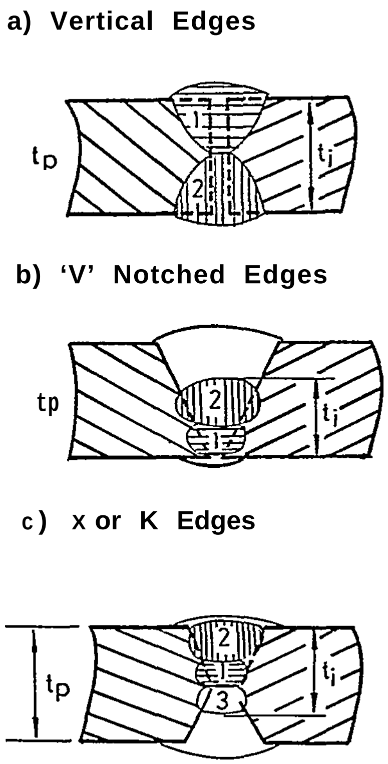

Fig. 5. Illustration of Butt Weld Cross Section Height t_i for Various Plate Edge Geometries [5].

b) One or two passes; welding under flux

$$q'_p = (1 - K_t K_f)\, q_p \tag{18}$$

c) Multipass welding; manual

$$q'_p = K_{pi}\, q_p \tag{19}$$

d) Multipass welding under flux

$$q'_p = K_{pi}\,(1 - K_t K_f)\, q_p \tag{20}$$

In equations (18), (20) the contraction coefficient K_t appears.

To estimate the contraction coefficient K_t, representing the effect of the plate thickness the heat intensity P is introduced.

The heat intensity P in Fig. 7 is calculated using:

$$P = p\eta_o\psi_o \frac{q'_p}{t_i^2} \quad (\text{cal/cm}^3) \tag{21}$$

where P is a coefficient given by

$$P = \frac{1450}{c\gamma T_m} \tag{22}$$

η_o is given in Fig. 8 as a function of e (eq. 16). ψ_o is given in Fig. 6B. The coefficient K_{pi} has to be found from Fig. 9 being a function of the weld pass number, N. Curve 1 corresponds to the values of the coefficient K_{pi} for X and K shaped plate edges. Curve 2 gives the coefficient for the V shaped plate edges, while curve 3 corresponds to the side opposite the weld pass for X and K shaped edges.

The values of the coefficient η_o can be found by performing several iterations since P depends on q'_p which is a function of K_t given by Fig. 7.

The coefficient s in Eq. (13) is determined from

$$s = 100 \frac{\alpha}{c\gamma\varepsilon_s} \tag{23}$$

where a = coefficient of linear expansion.

In this manner the angular deformation of the post butt welded plate can be estimated and the maximum out-of-plane deflection can be found using the corresponding Eqs. (1) or (2).

NUMERICAL EXAMPLE

In the representative example-we consider the angular deformation of a butt welded plate whose whickness is t_p = 14 mm (1 pass). The welding regine was:

d_e = 5 mm, 1 = 990 amp, U = 40 volts,

V = 35 m/hour

Automatic welding under flux.

The data based on the plate material is as follows:

a	=	12.7×10^{-6} 1/°C
c	=	0.13 cal/g °C
γ	=	7.85 g/cm^3
E_s	=	12×10^{-4}
$_0$	=	750 °C
a_o	=	0.068 cm^2/sec
p	=	1 η = 0.85

Solution

From (1o)we obtain q_p = 8300 cal/cam

From Fig. 3 K_f = 0.25

q'_f = (1 - K_f) q_p = 6230 cal/cm

$$\frac{q'_p}{t^2} = 3180 \text{ cal cm}^3$$

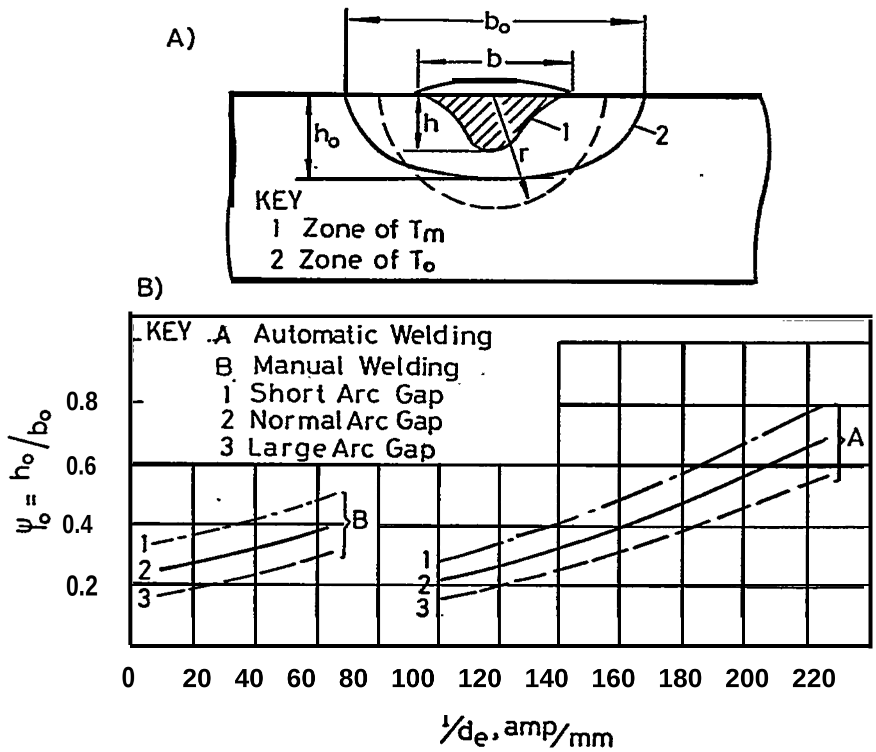

Fig. 6. Illustration of Zones Influenced by Welding [s].
A. Equivalent zone at yield temperature T_o T_m = melting temperature
B. Relative heating coefficient ψ_o versus current to electrode diameter ratio I/d .

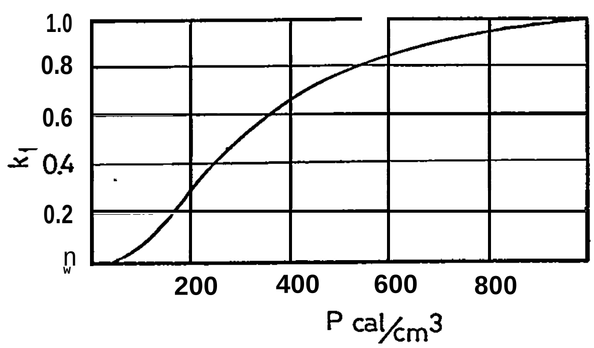

Fig. 7. Heated Plate Contraction Coefficient K_1 versus Heat Intensity Parameter p [5].

Fom Fig. 6B for I/d_e = 198 amp/mm ψ_o = 0.56

From Fig. 8 for $\varepsilon = \frac{q'_p V}{c\gamma T_o a_o}$=1270 η_o=0.23

From Fig. 7 for P = 410 cal/cm^3 K_1=0.72

From (18) q'_m = (1-0.25x0.72)8300=6800 cal/cm

Note that now a corrected value of η_o can be found.

From (23) s = 1

From (13) $S = s\psi_o\eta_o \frac{p}{2}$ = 450 cal/cm^3

From Fig. 4 ß= O if the plate restrained against bending B = 0.025 rad. the plate is not restrained.

Note that in the case when the plate is restrained against bending we have to check its stability after the edge restrictions are removed.

DISCUSSION AND CONCLUSION

This paper has illustrated the methodology adopted by the Soviet researchers in treating the estimation of post welded deformation of butt welded plates. The welding process was treated as an initial heat input which was modified by the process speed, weld pass, the presence of flux, etc. A numerical example has been presented to illustrate how this information is used.

While this is useful for practical work the framework illustrated in this paper can easily be extended to handle U. S. or European standard equipment such as welding

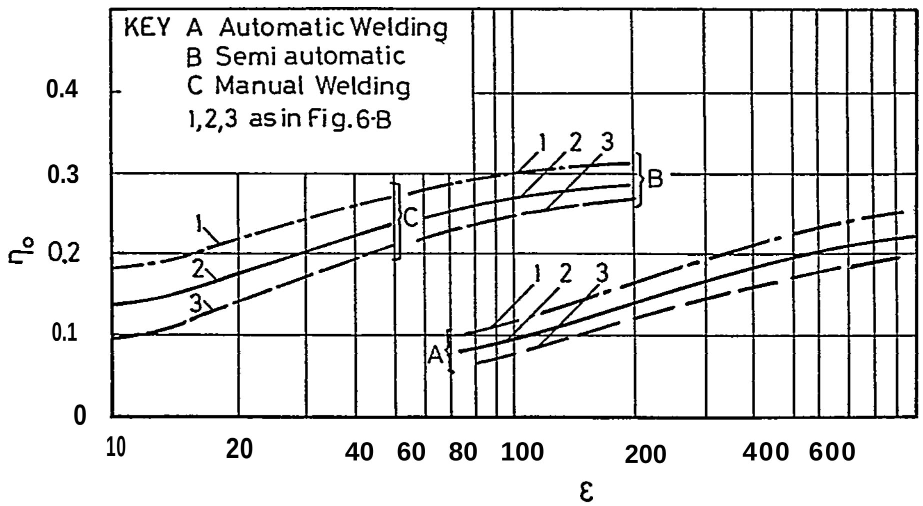

Fig. 8. Heat Transfer Efficiency η_o versus Heat Transmission Parameter ε [5].

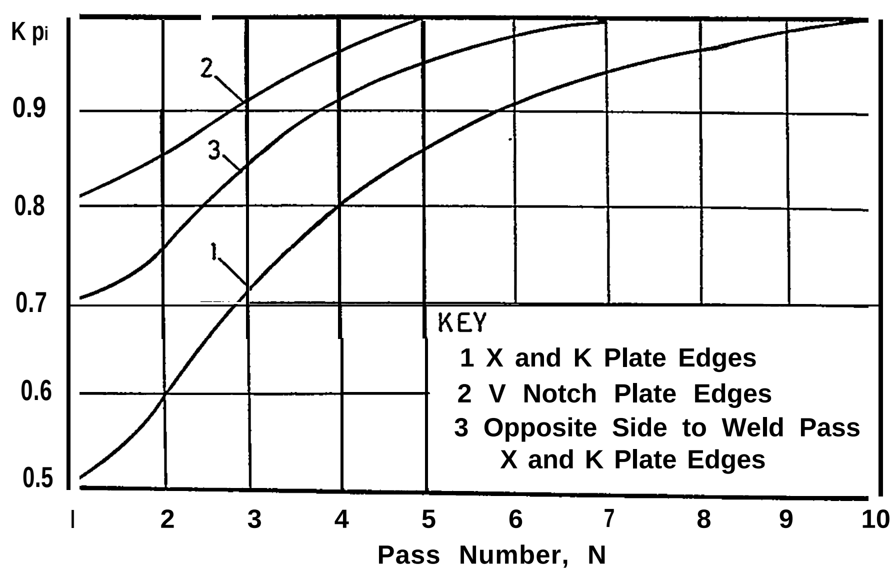

Fig. 9. Weld Pass Parameter K_p versus Weld Pass Number m [5].

rods and automated equipment speeds, welding current, etc. In this manner this work can be adopted in future automation and control schemes to obtain high quality welds with small defections.

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