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# Effect of Plastic Strains in the Shunting Zone on Force Parameters in the Butt Welding of Chain Links

**Abstract:** The article presents the development of a method enabling the calculation of force necessary to bend a chain link during butt welding, taking into consideration a plastic strain in the shunting zone. The study also discusses technological peculiarities concerned with the welding of single-contact chain links characterised by high bending rigidity and describes principles of the elastic-plastic strain of chain link shunting zone during bending. The work also contains the theoretical justification of the possibility of calculating the value of bending force based on the ultimate limit state and presents an analytical formula identifying the mathematical correlation between ultimate force, geometrical parameters and physico-chemical properties of the welded chain link material. Using an anchor chain as an example, the above-named analytical formula and the Finite Element Method were used to calculate the value of bending force, thereby confirming the reliability of the proposed method. It was ascertained that taking plastic strains into consideration significantly affected calculations results concerning the value of bending force during the butt welding of products having a closed shape and characterised by significant bending rigidity. The value of bending force calculated on the basis of the ideal elasticity of the anchor chain link material was higher (by more than an order of magnitude) than the value of the above-named force calculated taking into consideration plastic strains in the chain shunting zone.

**Keywords:** flash butt welding, link, chain, shunting zone, plastic strain, bending rigidity, ultimate limit state

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The flash single-joint butt welding of chain links differs significantly from the "conventional" single-joint welding of elements in an open system. As regards the nature of the process, the most similar process to the one mentioned above is the flash butt welding of metal strips, flywheel gears, wheel rims etc. [1, 2], the dimensions and circumference of which exceed linear dimensions of a welded cross-section tens or even hundreds of times.

In comparison with the welding of products in an open system and having similar cross-sections, the welding of chain links is characterised by energy losses resulting from the heating of a fully cross-sectional link segment shunting a joint being made; a low coefficient of

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welding machine power utilisation, a significant increase in consumed flashing power related to increased transformer no-load voltage, the necessity of preheating an element in order to increase the resistance of the shunting zone and decrease required deformation force when shaping a link using a bending device (Fig. 1). The above-named peculiarities are discussed in detail in works [3÷6].

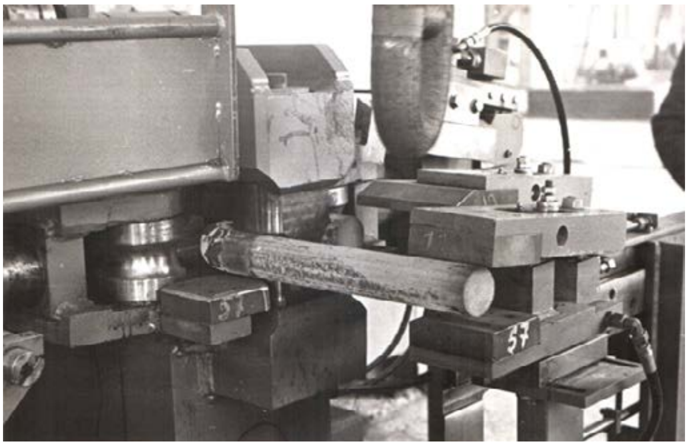

Fig. 1. Preparation of the chain link initial material using a bending machine (first bending) in a chain welding station (ESAB)

In addition, the single-joint welding of chain links is characterised by the generation of significant mechanical resistance in the shunting zone of a link subjected to welding and being a response to the effect of force responsible for deformation during flashing and upsetting. Because of the necessity of eliminating mechanical resistance exerted by the rectilinear segment of the chain, the welding machine upsetting system is not able to provide necessary upsetting force, thus leading to a decrease in an upsetting rate and, consequently, to the reduction of welded joint strength.

Because of the foregoing, some authors [7, 8] suggest that the link be made of two halves where two joints are subjected to welding at the same time. Such a solution eliminates the bending of the shunting zone, yet it is characterised by significant faults affecting both the strength and the dimensional accuracy of links [9].

Because of the fact that during the single joint welding of chain links the technological process and the dimensional deviations of the initial material affect the quality to a lesser degree than during the two-joint welding process [5], it is more convenient to determine the value of force used to bend the shunting zone and select welding equipment providing necessary force and enabling the obtainment of solid-state welds characterised by required quality.

For the first time it was suggested that the precise value of force used to bend the shunting zone of the link be identified assuming the ideal elasticity of the material and determined using the following formula [10]

$$P_B = \frac{\pi d^4 E}{8\left(\pi D_m + 4l\right) D_m^2}\delta_\Sigma \qquad (1)$$

where $E$ – modulus of elasticity of the material; $d$ – diameter of the initial material (chain calibre); $D_m$ – average diameter of the ring material; $l$ – length of linear segments; $\delta_\Sigma$ – sum of allowances for flashing and upsetting.

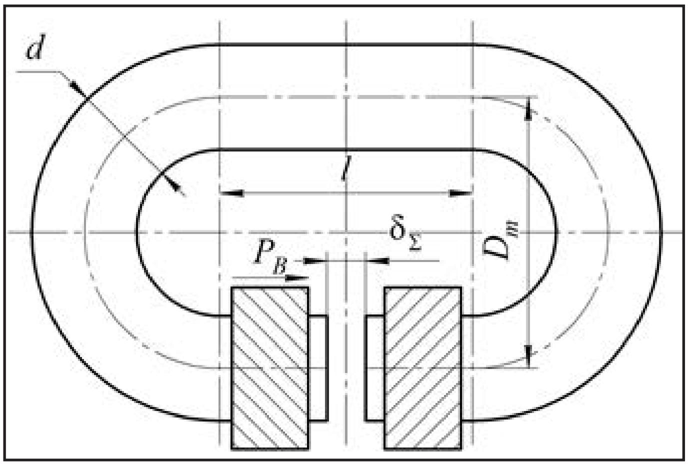


Fig. 2. Schematic fixing and pressing of a chain link during butt welding

According to data presented in work [10], the maximum bending moment during welding affects the linear segment of the shunting zone, situated opposite the joint (Fig. 2) and obtain the following constant value

$$M_{\max} = \frac{P_B \cdot D_m}{2} \qquad (2)$$

In such a case, maximum stresses in the shunting zone can be calculated on the basis of the well-known material strength-related formula [11]

$$\sigma_{\max} = \frac{M_{\max}}{W} = \frac{16P_B \cdot D_m}{\pi d^3} \tag{3}$$

Entering (1) to (3) results in the obtainment of the following formula

$$\sigma_{\max} = \frac{2d \cdot E}{\left(\pi D_m + 4l\right) D_m} \delta_\Sigma \tag{4}$$

Presented below is the calculation of maximum stresses generated during the continuous-flashing butt welding of the anchor chain link having a diameter of 22 mm and made of steel 20X, according to ISO 1704-91 (Table 1).

The performed calculations revealed that the maximum stress in the shunting zone, calculated assuming the ideal elasticity of the chain link material, exceeded (by an order of magnitude) the ultimate strength of steel 20X which at a temperature of 700°C amounted to 150 MPa [12]. In view of the foregoing, the link should break at an early stage of the welding process. However, the above assumption was not confirmed in practice and links were successfully made using the butt welding process. This could be ascribed to the fact that the calculation of the bending force using formula (1) did not allow for plastic strains generated in the shunting zone during butt welding. For this reason, the objective of the research work presented in the article was to investigate the effect of the above-named strains on the value of the bending force.

Computational methods were used to determine the correlation between the displacement of a moving clamp of the welding machine (making necessary allowances for flashing and upsetting $\delta_\Sigma$) and force necessary to bend the shunting zone. The displacement of the curvilinear bar was determined using the following formula [13]

$$f_i = \int_{(S)} \left( \frac{1}{\rho} - \frac{1}{\rho_0} \right) \cdot M_i dS \tag{5}$$

where $\rho_0$ – radius of the bar curvature before straining; $\rho$ – radius of the curvature of the bent bar; $M_i$ – equation of the bending moment in relation to unitary force acting in the direction of sought displacement.

Therefore, to identify the size of the displacement it was necessary to identify the correlation between the radius of curvature ρ and the bending moment beyond the limit of elasticity.

Work [14] presents the identification of the correlation between the bending moment and the curvature during the elastic-plastic bending of the curvilinear bar having the round cross-section and made of a material, the tension diagram of which is not characterised by hardening. The above-named correlation has the following form:

$$M = \frac{2M_T}{\pi} \cdot \frac{\rho_T \cdot (\rho_0 - \rho)}{\rho \cdot (\rho_0 - \rho_T)} \arcsin \frac{\rho \cdot (\rho_0 - \rho_T)}{\rho_T \cdot (\rho_0 - \rho)} + \frac{2M_T}{3\pi} \left[ 5 - 2 \left( \frac{\rho \cdot (\rho_0 - \rho_T)}{\rho_T \cdot (\rho_0 - \rho)} \right)^2 \right] \cdot \sqrt{1 - \left( \frac{\rho \cdot (\rho_0 - \rho_T)}{\rho_T \cdot (\rho_0 - \rho)} \right)^2}, \tag{6}$$

where $\rho_T$ – curvature of the bent bar, in relation to which plastic strains are generated; $M_T$ – bending moment, in relation to which the absolute value of the highest stress at points furthest from the neutral axis reaches the yield point of the material $\sigma_T$ and which, after taking

Table 1. Calculation of the maximum stresses in the shunting zone during the continuous-flashing butt welding of the anchor chain link having a diameter of 22 mm and made of steel 20X

| **Diameter of initial material (*d*), mm** | **Average diameter of ring fragment ($D_m$), mm** | **Length of linear segments (*l*), mm** | **Total allowance ($\delta_\Sigma$), mm** | **Modulus of elasticity (*E*), GPa** | **Maximum stresses ($\sigma_{max}$), MPa** |
|---|---|---|---|---|---|
| 22 | 57 | 53 | 10 | 143 | 2823 |

NOTE: Because of the fact that the initial material subjected to welding is heated, the value of elasticity modulus is related to a temperature of 700 °C.

into consideration formula (3) $M_T$, is expressed by the following formula:

$$M_T = \sigma_T \frac{\pi d^3}{32} \tag{7}$$

Equation (6) is transcendental in relation to $\rho$ as the unknown is an argument of the arcus sinus inverse trigonometric function. Such equations can only be solved using approximate methods [15]. Because of the foregoing, it was not possible to determine the explicit correlation between the bar curvature and the bending moment, affecting the cross-sections of the bar. However, previous tests [16] revealed that during the butt welding of chain links a decrease in their bendability $c$, i.e. a decrease in their bending rigidity, was accompanied by the bending force value nearing limit value $P_c$ (Table 2).

Table 2. Calculation results related to bending force during the pulsed-flashing butt welding of chain links made of steel 12X18H10T ($\sigma_T$ = 315 MPa)

| Mean diameter ($d_m$), mm | Height ($h$), mm | Bendability ($c$) | Bending force ($P_B$), kN | Ultimate force ($P_c$), kN | $P_B/P_c$, % |
|---|---|---|---|---|---|
| 370 | 50 | 23.25 | 10.12 | 10.64 | 95.11 |
| 410 | 50 | 25.76 | 10.61 | 11.52 | 92.10 |
| 602 | 92 | 20.56 | 29.85 | 31.01 | 96.26 |
| 566 | 80 | 22.23 | 27.10 | 28.50 | 95.09 |
| 592 | 110 | 16.91 | 51.07 | 51.51 | 99.15 |
| 390 | 40 | 30.63 | 13.13 | 14.22 | 92.33 |
| 397 | 35 | 35.63 | 10.53 | 12.15 | 86.67 |

The adopted parameter of closed-shape product bendability is the proportion of the circumference of lines of inertia centres of product cross-sections in relation to the value of the cross-section in the bending plane [5]. As a result, the above-named parameters are determined using the following formula:

– in relation to (chain) links having the rectangular cross-section

$$c = \frac{\pi d_m}{h} \tag{8}$$

where $d_m$ – mean diameters of the link; $h$ – height of the cross-section of the link;

– in relation to links having the round cross-section

$$c = \frac{\pi D_m + 2l}{d} \tag{9}$$

The analysis of the data presented in Table 2 revealed that where bending parameter $c \approx 17$, the value of bending force constituted more than 99% of the ultimate force. The forgoing justified the presumption that in relation to the test link having a diameter of 22 mm (Table 1), the bendability of which, in accordance with formula (9), amounted to $c \approx 13$, the difference between the bending force and the ultimate force was of little consequence. For this reason, it was necessary to identify the value of the ultimate force during the butt welding of the link.

According to work [17], force recognised as ultimate is the one in relation to which the height of the elastic area $h_T$ is significantly lower than cross-sectional diameter $d$ (Fig. 3). The above-named force is negligible after adopting an assumption according to which stresses are higher than the yield point at each point of the cross-section.

Work [14] presents the functional correlation between the height of the elastic area and the present curve of a bent bar having the round cross-section of the following form

$$\frac{h_T}{d} = \frac{\rho \cdot (\rho_0 - \rho_T)}{\rho_T \cdot (\rho_0 - \rho)} \tag{10}$$

After entering formula (10) into dependence (6), the following correlation between the bending moment and the height of the elastic area is obtained:

$$M = \frac{2M_t}{3\pi}\left\{3\frac{d}{h_T}\arcsin\frac{h_T}{d} + \left[5 - 2\left(\frac{h_T}{d}\right)^2\right]\cdot\sqrt{1-\left(\frac{h_T}{d}\right)^2}\right\} \tag{11}$$

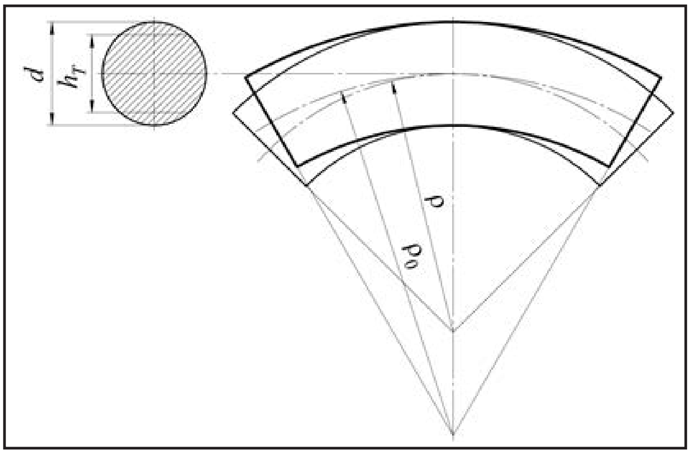


Fig. 3. Position of the elastic and plastic area in the section of the bent bar having a round cross-section during bending

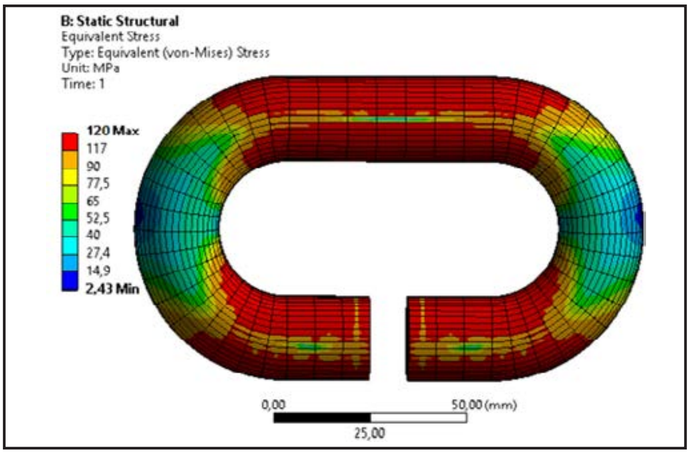


Fig. 4. Stress fields in the shunting zone of the anchor chain link having a diameter of 22 mm and made of steel 20X, triggered by the displacement of a moving welding element in relation to the total value of allowances (non-deformed shape)

In the ultimate limit state it is possible to ignore the $h_T/d$ ratio. Then, assuming that

$$\arcsin\frac{h_T}{d} \approx \frac{h_T}{d}$$

expression (11) after transformations takes the following form

$$M_c = \frac{16}{3\pi} M_T = \frac{\sigma_T \cdot d^3}{6} \qquad (12)$$

Taking into consideration the fact in the ultimate limit state $M_{max} = M_c$, as well as substituting formula (12) to formula (2), it was possible to obtain the following dependence identifying the bending force during the butt welding of chain links

$$P_B = P_c = \frac{\sigma_T \cdot d^3}{3D_m} \qquad (13)$$

In relation to the anchor chain link having a diameter of 22 mm (Table 1) and made of steel 20X ($\sigma_T$ = 120 MPa at a temperature of 700°C [12]), the value of bending force calculated using formula (13) amounted to 7.47 kN. The above-presented data were confirmed by the FEM-based numerical calculation results (Fig. 4), according to which sought force $P_B$ amounted to 7.407 kN = 0.9916 $P_c$. The difference between the analytical and numerical calculation results amounted to less than 1%.

The analysis of Figure 4 also confirmed the previously formulated assumption concerning the very small elastic area in comparison with the cross-section of the link. As can be seen, the rectilinear segment situated opposite the joint was nearly entirely located outside the limit of elasticity (red colour corresponds to the plastic area).

It should be noted that the bending force calculated using formula (1) was nearly 14 times higher than the value calculated taking into consideration plastic strains, using dependence (13). The foregoing revealed that in cases of closed-shaped products characterised by high bending rigidity, the calculation of force parameters of butt welding, after assuming elastic conditions, produces unsatisfactory results.

Based on the test results concerning the effect of the plastic strains in the shunting zone on bending force value during the butt welding of

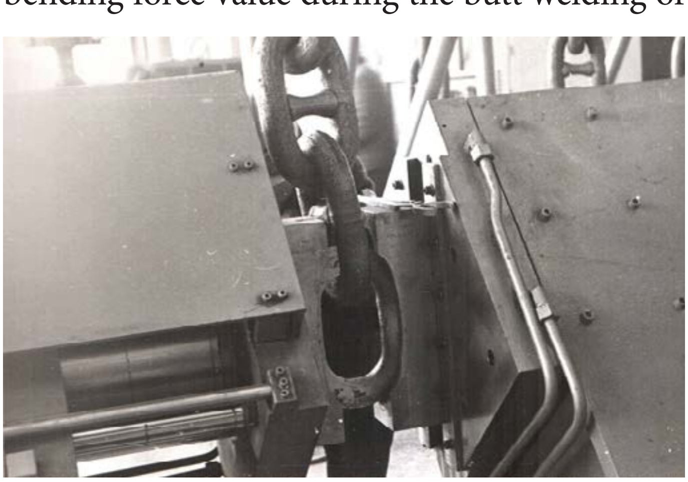

Fig. 5. Providing a butt welded chain link with required geometrical dimensions using the hydraulic press in an ESAB chain-making stand

ring-shaped products, it was proved and demonstrated mathematically that when bending force $P_B$ reached a value close to ultimate value $P_c$, the geometrical shape of a welded product would be deformed [16]. The above conclusion also refers to chain links as the geometrical shape deformed during welding is restored using a hydraulic press (Fig. 5).

## Conclusions

1. The tests led to the development of an ultimate limit state-based method enabling the calculation of force necessary to bend the shunting zone during the butt welding of closed-shape products characterised by high bending rigidity, e.g. anchor chain links.

2. The transformation of the equations describing the elastic-plastic bending of curved bars enabled the identification of the mathematical correlation between the value of the ultimate limit state and the geometrical dimensions and the physico-chemical properties of the chain link material during butt welding.

3. The chain link made of steel 20x and having a diameter of 22 mm was used when performing calculations concerning bending force, applying the proposed analytical method, and, in a numerical manner, using the Finite Element Method. It was demonstrated that the difference between the aforesaid bending force calculation results and measured values amounted to less than 1%, which confirmed the reliability and indicated the high accuracy of the proposed analytical method.

4. It was revealed that the bending force calculated assuming the ideal elasticity of the material of the anchor chain link was nearly 14 times higher than the value of the bending force calculated taking into consideration plastics strains in the chain shunting zone. This fact justifies the conclusion of the unacceptability of the calculations concerning the force parameters of the butt welding of closed-shape products characterised by high bending rigidity.

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