Influence of the scale factor on the mechanical properties of heterogeneous welded joints

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Abstract. The influence of the scale factor on the strength properties of welded products with pronounced mechanical inhomogeneity presented in the formation of a soft zone was investigated. Dissimilar welded joints were performed by electron beam welding and consisted of 12Kh18N10T austenitic steel and low-carbon ferritic steel. Interrelation of the ultimate tensile strength of the welded joints and the relative width of the soft zone was obtained for samples of three different scale levels. The growth in strength properties with a proportional decrease in the dimensions of the welded products was indicated.

1. Introduction

Manufacturing of most industrial products usually consists of numerous stages to finally achieve the desired product. In some cases, it is not enough just to produce individual components. There is a high demand in implementing joining processes such as welding, brazing, soldering, bolting, etc. In industrial-scale assembly purposes, welding is overwhelmingly employed due to its benefits. For instance, the use of dissimilar welded joints of metals and alloys can significantly reduce the cost by less application of expensive materials; achieve the desired properties of products, and decrease the weight of structures. However, it should be borne in mind that dissimilar welded joints are often characterized by considerable structural inhomogeneity, which may critically affect the distribution of strength properties and bearing capacity of the entire construction.

The nature of this heterogeneity can be completely different. A soft layer in welds may occur when welding cold-worked alloys, precipitation hardening materials, as well as when joining martensitic steels by an austenitic weld. A common phenomenon is the formation of a soft interlayer in the heat-affected zone (HAZ) because of carbon diffusion in dissimilar welding [1–3]. Such low strength layers basically lead to the weakening of the whole welded product. Therefore, it is necessary to control the mechanical properties and stress state of heterogeneous welded joints, taking into account the geometric parameters of the soft zones (SZ). Namely, these parameters can cause significant influence and determine the maximum load capacity of the entire assembly.

If welded joints with soft interlayers are loaded, plastic deformation will be constrained along the contact surfaces (fusion boundaries) by metal with higher strength properties. As a result, a volumetric stress state of a weld arises, and the constraint effect is demonstrated. Investigation of this phenomenon makes it possible to increase the strength of a dissimilar welded joint with SZ up to the level of the base metal.
Currently, many papers are devoted to the study of the constraint effect. Of particular interest is the investigation of the key parameters of the constraint effect. Almost all of them provide a great effect on the strength of mechanically inhomogeneous welded joints. Nowadays, the most widely studied parameter is the relative width of the soft zone $\chi_{SZ}$ equaled to the ratio of the soft layer width to the thickness of the welded product. Referring to the experimental and numerical studies in [6–11] it can be seen that the significant contribution of the constraint effect to the strength characteristics is possible only if the relative width of the SZ does not exceed a certain threshold value. For example, following on from the study of W. Maurer et al. [10], the threshold value constituted to 0.25, while F. Hochhauser et al. [9] set this value equal to 0.33. Also, there are other important factors such as welding groove type, angle of the bevel, size of weld reinforcement, the shape of a soft zone, mismatch ratio, and a change in the compactness degree of the cross-section of the welded products. All these parameters can considerably alter the strength properties of the weld, its plasticity, and even the nature of fracture [12].

The authors of this current paper have considered one more parameter – the scale factor of the welded products. There is an assumption that it also contributes to a significant strengthening of mechanically inhomogeneous welded joints. Inspired by the analysis of other scientific papers where the main attention was paid to the study of dimensionless parameters on the constraint effect, this research will be focused on the real geometry of the studied welded joints. Thus, the experimental part will contain tests with welded tensile samples of different scales, but with an identical relative width of the soft zone $\chi_{SZ}$. If the results of mechanical characteristics vary from one scale to another, this fact will explain the difference in the early recorded threshold values of the SZ relative width in highly discussed papers. The main aim of the paper is to establish the influence of the scale factor on the strength properties of heterogeneous welded joints with a soft zone.

2. Materials and Methods
To investigate the impact of the scale factor on the strength of dissimilar welded joints, it was decided to produce welded products of different scales. Those products were made of 12Kh18N10T austenitic steel and an intermediate soft zone of low-carbon steel with a ferrite structure. As a soft material, a plate with a hardness of 96 HB was used. It was welded to the base metal of austenitic steel by two welded joints performed by electron beam welding. To satisfy all the requirements for assembly accuracy during electron-beam welding (EBW), the welded edges of all plates were pre-milled to obtain high geometric precision.

Selection of welding modes was done in order to obtain dissimilar welded joints from austenitic corrosion-resistant and ferritic stainless steel with parallel or close to this shape weld walls. Namely, this geometry of the welded joints is needed to study the constraint effect. The welding modes were developed based on experimental tests carried out on plates with thicknesses of 16, 6, and 4 mm, electron-beam gun included an ELA-40I power unit with an accelerating voltage of 60 kV and a maximum power of the electron beam – 40 kW. By adjusting the parameters such as work distance $l$, welding speed $V_w$, beam current $I$, and focus coil current $I_f$, welds with parallel walls were ultimately obtained. Parameters of the selected welding modes are shown in Table 1.

| Plates thickness, mm | $l$, mm | $V_w$, mm/min | $I$, mA | $I_f$, mA | $d$, mm | $x$, mm |
|---------------------|---------|---------------|---------|-----------|---------|---------|
| 16                  | 265     | 500           | 100     | 734       | 0.2     | 3.5     |
| 6                   | 155     | 1000          | 50      | 780       | 0.25    | 4       |
| 4                   | 155     | 1000          | 30      | 780       | 0.25    | 4.5     |

Despite the fact that using the selected modes allow to achieve parallel weld walls (the angle between the fusion boundaries is about 1.5–2°), the formation of a vertical weld wall from the side of the ferritic steel was realized only with an electron beam deflection from the vertical axis at angle $a/2$.
(Figure 1). The angle a/2 was determined without taking into account the upper extended part of the weld.

![Diagram of electron beam deflection](image1.png)

**Figure 1.** Scheme of electron beam deflection implemented to attain parallel walls of the weld from the ferritic steel side. F – ferritic steel, A – austenitic steel.

After the EBW mode was developed, the welded plates were fixed using tack welds performed by gas tungsten arc welding (GTAW). Next, this welded assembly was demagnetized and installed in a vacuum chamber to perform EBW. Moreover, it was fixed with four clamps to minimize welding deformations. The welded joints were done sequentially with an intermediate pause not to overheat the final welded product. Application of ferritic plates of varied thickness led to the formation of welded products with a soft zone width of 0.1 to 10 mm. Quality control of welded joints was carried out by visual inspection and metallographic studies on transverse microsections, which were made from the initial and final sections of each weld.

Metallographic analysis revealed the formation of quenching structures (Figure 2) from the side of the ferritic steel due to dissolution during heating of tertiary cementite and then rapid cooling.

![Microstructure of HAZ](image2.png)

**Figure 2.** Microstructure of the HAZ from the side of low-carbon steel, 200x.

The structural inhomogeneity led to an increase in the hardness in the HAZ from 110 HV1 to 150 HV1. To equalize the hardness in the ferritic steel after electron beam welding, the structure was
tempered at 700°C for 2 hours. This regime of heat treatment (HT) made it possible to reduce the hardness of the heat-affected zone to the average hardness of the ferritic zone (Figure 3).

After HT, the welded product was mechanically processed to get tensile specimens. Thus, three series of the specimens of different scales were produced:

- 10 mm thickness with a ferrite zone width from 1 to 10 mm;
- 3 mm thickness with a ferrite zone width from 0.1 to 6 mm;
- 1 mm thickness with a ferrite zone width from 0.4 to 1.5 mm.

Next, tensile specimens were tested on an Instron 8801 testing machine to determine the strength properties of the heterogeneous welded products.

### 3. Results and Discussion

The ultimate tensile strength (UTS) of welded specimens of different scales with varying $\chi_{SZ}$ was registered during tensile stress tests and these results are finally presented in Table 2. Visual representation of the interrelation between the strength properties of mechanically inhomogeneous welded joints and the relative width of the SZ is depicted in Figure 4.

Thus, it follows from Figure 4 and Table 2 that the strength of dissimilar welded joints is influenced not only by the value of the dimensionless parameter - the relative width of the SZ but also by the size of the welded product. According to the experiments, for specimens with a thickness of 3 mm, it was shown that the ultimate tensile strength can be achieved to the level of the base metal at $\chi_{SZ} < 0.2$. However, it should be noted that such a similar effect for specimens 1 mm thick can be attained with a larger relative width of the SZ. Therefore, it can be concluded that the constraint effect is greater in small-sized welded products than in large-sized ones with the same relative width of the soft zone.

Such a noticeable increase in the strength characteristics of a 1 mm specimen in comparison with 3 mm and 10 mm ones may be explained due to the large impact of the work-hardened surface layer formed during milling of specimens for tensile tests. The smaller the specimen thickness, the larger the relative cross-sectional area the work-hardened layer takes. As a result, the growth in the total level of mechanical properties of the welded product has occurred.

Further research in this field of study is likely to be focused on the statistical reliability of the obtained results and testing samples with a removed work-hardening surface layer.
Table 2. The results of mechanical properties of dissimilar welded structures with different thickness (B).

| Specimen thickness, $B=10$ mm | Specimen thickness, $B=3$ mm | Specimen thickness, $B=1$ mm |
|-------------------------------|-------------------------------|-------------------------------|
| UTS, $\sigma_U$ kg/mm$^2$ | The relative width of the SZ, $\chi_{sz}$ | UTS, $\sigma_U$ kg/mm$^2$ | The relative width of the SZ, $\chi_{sz}$ | UTS, $\sigma_U$ kg/mm$^2$ | The relative width of the SZ, $\chi_{sz}$ |
| 0 < $\chi$ < 0.1        | 606.2                          | 0.014                         | 607                             | 0.177                         |
|                          | 609.1                          | 0.020                         | 594.8                           | 0.186                         |
|                          | 576.9                          | 0.022                         | 583.2                           | 0.027                         |
|                          | 627.5                          | 0.030                         | 601.6                           | 0.031                         |
|                          | 600.6                          | 0.050                         |                                  |                               |
| 0.1 ≤ $\chi$ < 0.2     | 575.4                          | 0.100                         | 607                             | 0.177                         |
|                          | 575.8                          | 0.104                         | 594.8                           | 0.186                         |
| 0.3 < $\chi$ < 0.5     | 504.3                          | 0.369                         | 479.3                           | 0.426                         |
|                          | 508.9                          | 0.371                         | 504.5                           | 0.451                         |
| 0.5 < $\chi$ < 0.7     | 457.9                          | 0.573                         | 467                             | 0.584                         |
|                          | 473                            | 0.595                         | 460.8                           | 0.636                         |
| 0.9 < $\chi$ < 3.1     | 402                            | 0.985                         | 415.1                           | 0.975                         |
|                          | 403.3                          | 0.991                         | 419.4                           | 0.981                         |
|                          | 423.3                          | 1.092                         | 456.5                           | 1.888                         |
|                          | 412.1                          | 1.093                         | 455.4                           | 2.209                         |
|                          | 408.3                          | 1.920                         | 406.4                           | 3.089                         |
|                          | 407.7                          | 1.944                         |                                  |                               |
|                          | 395                            | 2.184                         |                                  |                               |
|                          | 401.6                          | 2.223                         |                                  |                               |

Figure 4. The dependence of the ultimate tensile strength of the welded product on the relative width of the SZ for different scale welded samples.
4. Conclusion
Analysis of the preliminary results reveals the interrelation between the strength characteristics of mechanically inhomogeneous welded joints and their dimensions. It was shown that the constraint effect rises with a decrease in the welded products size. With the same values of the relative width of the SZ, the strength of small welded products was recorded 25% higher than that of larger products.

To conclude, when designing dissimilar welded joints in industrial products, it is necessary to take into account the influence of the scale factor on the strength characteristics.

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