Effect of ultrasonic impact treatment on redistribution of residual stresses in dissimilar thickness girth welds

M M Sidorov\textsuperscript{1} and N I Golikov\textsuperscript{1}

\textsuperscript{1}Larionov Institute of Physical and Technological Problems of the North, the Siberian Branch of the Russian Academy of Science, Federal Research Center ‘Yakut Scientific Center of the Siberian Branch of the Russian Academy of Sciences’, Yakutsk, Russia, 677980

E-mail: sidorovmm@bk.ru

Abstract. Effect of repeated ultrasonic impact treatment on redistribution of residual stresses in a dissimilar thickness girth butt weld of pipes with a diameter of 530 mm of low alloyed (0.9\%C-2\%Mn-1\%Si) steel was studied. Residual stresses were measured by the X-ray method based on measurement of microdeformation of a crystal lattice of a material under its influence. The research results showed that tensile residual stresses in the girth weld were formed at the inner side of the pipe after welding. Ultrasonic impact treatment of the weld at the inner side caused complete transformation of residual stresses from tensile to compressive ones when speed was in the range from 0.06 to 0.12 m/min. However, reduce in speed of treatment down to 0.04 m/min gave a negative effect. The values of compressive residual stresses in heat affected zone on the side of the thinner pipe were decreased.

1. Introduction

As a rule, tensile residual stresses are present in welded joints and adversely affect their fatigue strength [1, 2]. This negative factor is not always possible to minimize using technological processes before or during welding. Therefore, post-weld treatment of welds is required in many cases. Sometimes, post-weld treatment is necessary to reduce tensile residual stresses. Various methods and devices are used for this purpose [3–6]. Ultrasonic impact treatment (UIT) is one of the most effective and widely spread among post-weld treatment methods.

A principle of the UIT operation is based on impact of low-frequency ultrasonic vibrations of a vibro-impact tool on the surface of a welded joint. As a result, redistribution of hazardous tensile residual stresses to compressive ones occurs on the treated surface [7–9]. It is known that compressive residual stresses improve fatigue strength of welded joints.

Investigation of redistribution of residual stresses in welded joints before and after treatment is a rather laborious process. It is not always possible to predict how residual stress fields will be formed after treatment. The result depends on joint dimensions, residual stresses, energy input, duration and a method of treatment. Therefore, research in this direction is an urgent task. This may help correctly apply promising processing technologies in practice and extend lifecycle of critical welded structures.

The purpose of this paper is to study the effect of repeated UIT on redistribution of residual stresses in dissimilar thickness girth welds.

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2. Materials and methods
A girth butt weld of pipes with a diameter of 530 mm was investigated. The wall thickness of the pipe No.1 was 10 mm, the pipe No.2 was 8 mm (Figure 1). Both pipes were of low-alloyed (0.9%C-2%Mn-1%Si) steel. The pipes were joined by shielded metal arc welding. The number of passes was three (root, intermediate and cover). Mean values of mechanical properties of the base metal and the weld metal are given in Table 1. Chemical composition the pipe metals based on the results of spectral analysis as well as Russian State Standard GOST 19281-2014 are presented in Table 2. The results of mechanical tests and spectral analysis were obtained using facilities of the Center for Collective Use ‘Station of low-temperature tests’ (Larionov Institute of Physical and Technological Problems of the North, the Siberian Branch of the Russian Academy of Sciences).

![Figure 1. Scheme of the edge shapes and the dissimilar thickness girth weld.](image)

| Material | Yield strength $\sigma_T$, MPa | Ultimate tensile strength $\sigma_B$, MPa | Percent elongation $\delta_{0.5}$, % | Impact strength $a$, J/cm$^2$ |
|----------|-------------------------------|----------------------------------------|-------------------------------------|--------------------------------|
| Base metal of the pipe No.1 (wall thickness of 10 mm) | 560 | 668 | 27 | 109 |
| Base metal of the pipe No.2 (wall thickness of 8 mm) | 463 | 585 | 32 | 152 |
| Weld metal | 486 | 609 | 24 | 89 |
| Fusion zone | - | - | 55 | 22 |

| Material | Chemical composition, % |
|----------|--------------------------|
| C | Si | Mn | Cr | Ni | Al | Mo | P | S | Cu | Fe |
| Base metal of the pipe No.1 | 0.10 | 0.57 | 1.31 | 0.12 | 0.12 | 0.03 | 0.02 | - | - | 0.20 | Bal. |
| Base metal of the pipe No.2 | 0.12 | 0.50 | 1.41 | 0.03 | 0.03 | 0.03 | 0.02 | - | - | 0.03 | Bal. |
| Steel 0.9%C-2%Mn-1%Si according to Russian State Standard GOST 19281-2014 | ≤0.12 | 0.5-0.8 | 1.30-1.70 | ≤0.30 | ≤0.30 | - | - | ≤0.03 | ≤0.04 | ≤0.30 | Bal. |
UIT was done using a special technological setup. It consisted of an UZGT 0.5/27 ultrasonic generator and a ‘Bumblebee’ unit at the inner side of the pipe wall. The method was described in detail in [10]. Each surface area was treated three times at different speeds and, as a result, with different performance (Table 3). Residual stresses at the outer and inner sides of the girth weld were measured after each treatment.

**Table 3. Parameters of the UIT process**

| Treated surface area                                                                 | Treatment time and speed |
|--------------------------------------------------------------------------------------|--------------------------|
| Section (60 mm long and 40 mm wide) symmetrically to the weld axis                   | UIT-1 | UIT-2 | UIT-3 |
|                                                                                        | 30 s  | 30 s  | 30 s  |
|                                                                                        | 0.12 m/min | 0.06 m/min | 0.04 m/min |

Residual stress fields in the girth weld were determined by X-ray method [11]. Stresses were measured in the axial (σ_z) and circumferential (σ_θ) direction relatively to the pipe axis at points located at different distances from the weld center (the maximum distance was 20 mm). The measurement scheme is shown in Figure 2. Before measurement, the tested surface was cleaned, manual ground, and etched to a depth of 200 μm with a mixture of concentrated nitric and hydrochloric acid in a ratio of 1:3 to remove the deformed layer.

![Figure 2](image.png)

**Figure 2.** Scheme of measurement of residual stresses at the outer and inner sides of the weld.

3. Results and discussion

The results of measurement of residual stresses at the outer and inner sides of the weld before treatment are shown in Figures 3 and 4. Figure 3 shows compressive residual stresses at the outer side of the girth weld in the circumferential and axial directions which were formed during welding. Compressive residual stresses in heat affected zone (HAZ) on the side of the pipe No.2 were higher than on the side of the pipe No.1.

![Figure 3](image.png)

**Figure 3.** Distribution of axial (a) and circumferential (b) stresses in the girth weld at the outer side: Z is distance from the weld axis, 1 is the pipe with a wall thickness of 10 mm; 2 is the pipe with a wall thickness of 8 mm.
Tensile residual stresses were observed at the inner side of the weld. Their values in HAZ on the side of the pipe No.2 were also higher than on the side of the pipe No.1 (Figure 4). The obtained results show that wall thickness of the pipes played an important role in formation of axial and circumferential stresses in the weld. The highest compressive and tensile residual stresses were formed in the pipe with a thinner wall as it had been more heated and deformed during welding.

![Figure 4. Distribution of axial (a) and circumferential (b) stresses in the girth weld at the inner side: Z is distance from the weld axis, 1 is the pipe with a wall thickness of 10 mm; 2 is the pipe with a wall thickness of 8 mm.](image)

Figure 5 shows redistribution of residual stresses at the inner side of the weld after the first UIT. Axial and circumferential stresses partially transformed into compressive ones. Tensile residual stresses remained at the level of 20-50 MPa on the side of the pipe No.1 at a distance of 20 mm from the weld axis.

![Figure 5. Distribution of axial (a) and circumferential (b) stresses in the girth weld at the inner side after UIT-1: Z is distance from the weld axis, 1 is the pipe with a wall thickness of 10 mm; 2 is the pipe with a wall thickness of 8 mm.](image)

Complete transformation of tensile residual stresses to compressive ones, as well as an increase in the level of compressive residual stresses obtained after the first treatment, occurred after the second UIT at a speed of 0.06 m/min (Figure 6).
Figure 6. Distribution of axial (a) and circumferential (b) stresses in the girth weld at the inner side after UIT-2: Z is distance from the weld axis, 1 is the pipe with a wall thickness of 10 mm; 2 is the pipe with a wall thickness of 8 mm.

Redistribution of residual stresses at the inner side of the weld after the third UIT is shown in Figure 7. The values of compressive residual stresses increased over 300 MPa in the weld and HAZ on the side of pipe No.1. This caused a decrease in compressive residual stresses in HAZ on the side of the pipe No.2. Based on these results, it can be concluded that the UIT of the dissimilar thickness girth weld with a speed of 0.04 m/min gave a negative effect. Therefore, wall thickness of the pipes and distribution of residual welding stresses should be taken into account when treating this type of welds. Also, the results of the study showed that the level of residual stresses at the outer side of the weld were almost unchanged after UIT at the inner side.

Figure 7. Distribution of axial (a) and circumferential (b) stresses in the girth weld at the inner side after UIT-3: Z is distance from the weld axis, 1 is the pipe with a wall thickness of 10 mm; 2 is the pipe with a wall thickness of 8 mm.

4. Conclusions
The following conclusions can be drawn from the obtained results:
1. Compressive residual welding stresses were found in the dissimilar thickness girth weld of low alloyed (0.9%C-2%Mn-1%Si) steel at the outer side but tensile stresses were on the inside. The values of tensile residual stresses were higher by 40-50% in the thinner wall pipe than in the thicker wall one.
2. Ultrasonic impact treatment of the girth weld at the inner side of the pipe caused transformation of residual welding stresses from tensile to compressive ones. As a result of such treatment, the maximum compressive residual stresses reached values of -200…-300 MPa.
3. Reduce in speed of ultrasonic impact treatment of the dissimilar thickness girth weld to 0.04 m/min gave a negative effect. The values of compressive residual stresses in heat affected zone on the side of the thinner pipe were reduced.

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