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Analysis of Microstructure and Mechanical Properties of Wrought Iron

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Several wrought iron samples cut out from an old bridge built in 1910 in Šilutė have been received for metallographic examination and mechanical testing. The bridge still caries a local traffic, but it needs urgent repair, thus, the yielded information on material characteristics is of high importance.

The results of our examination of these specimens are presented in the paper. A metallic matrix of the specimens is very low in alloying elements (C, Si, Mn, Cr, Mo, S, etc.) with the exception of phosphorus (ca 0.15 %) and copper (ca 0.1 %), however, it contains a sufficient amount of slag inclusions. Fibre-shaped slag inclusions distributed in a metallic matrix have a certain influence on mechanical properties, particularly on plastic behaviour of wrought iron. The results of tensile strength of the examined specimens are similar to the respective properties of modern steel containing ca 0.1…0.15 % C, but the plastic behaviour of the wrought iron specimens differs highly from plasticity of modern steel. The arc welding of wrought iron has also been tested and the obtained results are discussed in the paper.

Keywords: wrought iron, microstructure, mechanical properties, chemical composition, weldability.

1. INTRODUCTION

Mechanical and technological characteristics are pretty well established for the modern steels, while a lack of important data for many wrought iron properties is evident. The use of wrought iron in wire, cables and pipe production, architecture, etc., is well known [1, 2]. Many of these objects are still in use, for example, as the oldest in the world Wheeling Suspension Bridge built in 1849 in the U.S.A [3], and many others. Hence, the investigation work to obtain data for use in reparational works of the objects built of wrought iron and for checking the materials suitability for subsequent service is of indubitable importance.

Some wrought iron samples cut out from the components of an old bridge built in 1910 in Šilutė have been examined in this work. The metallographic analyses and mechanical testings of the samples have yielded the important information on microstructure and the mechanical properties of the bridge material.

2. METHODS OF EXAMINATION

The *metallographic examination* of the specimens was performed by optical microscopes LMA-10, МИМ-8 and МБС-9. The specimens cut out of the bridge were mounted in a holder and prepared in the usual manner by grinding and polishing procedures. The composition of a metallic matrix, the size and form of the grains, distribution and shape of slag inclusions were analyzed in the course of examination. A general view of slag inclusions was observed on non-etched surfaces of the specimens, while a metallic matrix was analyzed on the specimens etched by Nital solution.

Microhardness of a metallic matrix was tested by means of apparatus ПМТ-3 with a standard square based pyramid and applied 200 grammes load.

The *chemical composition* of the specimens was analyzed by device Spektrolab LAV L7.

Mechanical tests are employed in this work in order to obtain data on mechanical properties of the bridge material.

Static tests. In the static tests the original thickness of the components of the bridge was preserved. Thus, the thickness of the specimens had the original dimensions of the bridge component. The specimen for static tests is shown in Fig. 1.

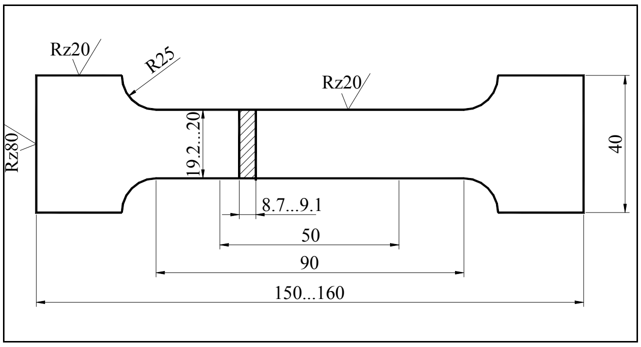

Fig. 1. Specimen for static tests of wrought iron

The static tests of wrought iron were made by means of static test machine of 10 metric tons (Type RM 104).

Notch impact tests. The Charpy V-notch impact test method was used. The use of 45°, 2 mm deep notch gives a greater test piece area below the notch but this has proved to be no disadvantage. The size of test pieces and of notches is described in the standards. The stringency of this test approximates to the severity of loading likely to be encountered by engineering structures and certain conditions. In addition, there is a marked energy drop, between ductile and brittle fractures, with this type of test that makes the limits of a transition range relatively easy to determine [4].

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The possibility of the arc welding of the specimens cut out from the bridge was tested by using AV-21 type electrodes (classification: ISO 2560: E51 2 RR 22; flux type: thick rutile-covering) and welding current of $I = 90...125$ A [5]. Mechanical properties of the welded seam according to the certification are represented in Table 1.

Table 1. Mechanical properties of welded seam [5]

Yield strength σ_Y, MPa	Tensile strength σ_U, MPa	Elongation δ, %	Notch impact strength KCV, J/cm^2
472	526	26	90

The electrodes containing 0.08 % C, 0.4 % Si, 0.6 % Mn, 0.018 % P and 0.008 % S are particularly suitable for welding mild steel sheets and other fabrications.

3. RESULTS AND DISCUSSIONS

3.1. Microstructure

Wrought iron is relatively pure iron, but in addition, it contains some amount of the refining slag, entrapped into the structure [6]. Actual density of the examined specimens amounts to 7.74 g/cm^3 while density of the ingot iron is slightly higher and reaches 7.87 g/cm^3. The lower density of wrought iron is associated with the residual slag inclusions entrapped into the structure of a metallic matrix (Fig. 2).

Wrought iron was usually made by smelting pig iron and oxidizing it with iron oxide in a puddling furnace. Therefore, the refined iron was obtained in the pasty state containing appreciable quantities of slag phase, principally iron silicates [7]. There is a certain uniformity in the slag composition and physical characteristics due to the limitation of a successful refining process. Taking into consideration the average density of fayalitic slag (ca 3.5 g/cm^3) and the density of tested specimens (7.74 g/cm^3) we have calculated the content of slag inclusions in the examined wrought iron and have found them amounting ca 2.5 wt. %, while wrought iron of high quality (two steps of refining) contains only from ca 1 wt. % to 2 wt. % of slags [2, 6].

The slag inclusions consisting of fayalite, glassy phase and free wustite (FeO) are rather evenly distributed along a metallic matrix of the examined specimens. Great majority of inclusions are of an elongated shape indicating the direction of plastic deformation caused, undoubtedly, by a rolling process. Their size ranges from the very small inclusions with an average thickness of a few micrometers to rather big ones. The extent of the largest inclusions amounts to ca 900 – 1000 μm in length and up to ca 250 – 300 μm in thickness.

Microstructural evidence and analyses of chemical composition have shown the low carbon metallic matrix composed of ferrite grains. The relatively fine equiaxial grains (the average grain size corresponds to ASMT No.6 – No.7) show both temperature and rate of recrystallization which has followed the rolling process to be proper.

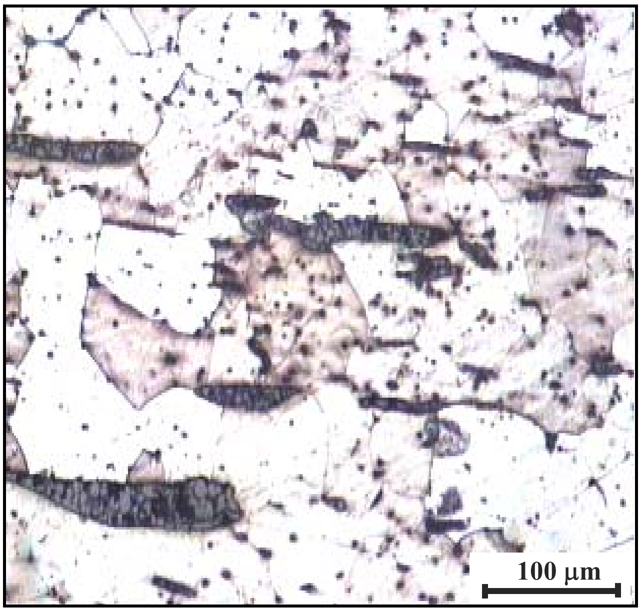


Fig. 2. The microstructure of the wrought iron specimen of the Šilutė bridge: a metallic matrix consisting of the ferrite grains (light) and the slag inclusions (variegated gray, dark)

Carbon content in the analysed specimen is very low, not exceeding 0.01 %. A metallic matrix of the specimen is also low in alloying elements: 0.05 % Si, 0.06 % Mn, 0.07 % Ni, 0.014 % Mo, 0.006 % Cr, 0.007 % V, 0.01 % S. Only phosphorus and copper demonstrate slightly greater content (ca 0.15 % P and ca 0.1 % Cu), that helps certain increase in the strength of iron. Such elements as copper and nickel can be reduced from their oxides more easily than iron and they enter into solid solution in reduced iron during the smelting process [8]. The reduction of silicon and manganese from their oxides is more difficult than that of iron, therefore the greater part of Si and Mn remains in slag [7, 9].

Rather high microhardness HV_{200} of a metallic matrix ranging from ca 1600 MPa to ca 2000 MPa most probably is influenced by solid soliution of phospforus in ferrite and by other elements even in negligible concentrations.

3.2. Static tests

Generally, the strength of the materials depends upon the grains and slags relation and on the possibilities of deformation [10]. The slag inclusions entrapped in the structure, if distributed correctly, confer appreciable strength on pure, soft iron [11].

The elastic and plastic properties of wrought iron depend on the variety of its microstructure. The phenomenon of static fracture is of an intermediate character between plastic and brittle processes of specimens due to heterogeneity of wrought iron. The results of the mechanical properties of the tested wrought iron are shown in Table 2. The slag inclusions prevent longitudinal and transverse strains of wrought iron and decrease elastic ones. Thus, great difference of micro-strains of the ferrite grains and the slag inclusions results in the appearance of the layers in the static fracture (Fig. 3).

Strength parameters σ_Y and σ_U of the Šilutė bridge components demonstrate rather high values, while

Table 2. Mechanical properties of wrought iron

Parameter	Wrought iron from Šilutė bridge				Wrought iron [2]	Ingot iron (C = 0.02 %) [1]	Mild steel St.15 [12]
	Specimen No.1	Specimen No.2	Specimen No.3	Average meaning			
Yield strength σ_Y, MPa	283	286	242	270	232	131	220
Tensile strength σ_U, MPa	378	384	355	372	341	289	370
Elongation δ, %	12.0	14.0	19.7	15.0	28.0	48.0	27.0
Reduction of area ψ, %	12.3	13.6	29.2	18.0	48.0	-	55.0

elongation δ and reduction of the area ψ are much lower comparing with other materials shown in Table 2. The results of the static test show that the wrought iron specimens bear the strength resembling to the steels with the quantity of carbon 0.1…0.15 %.

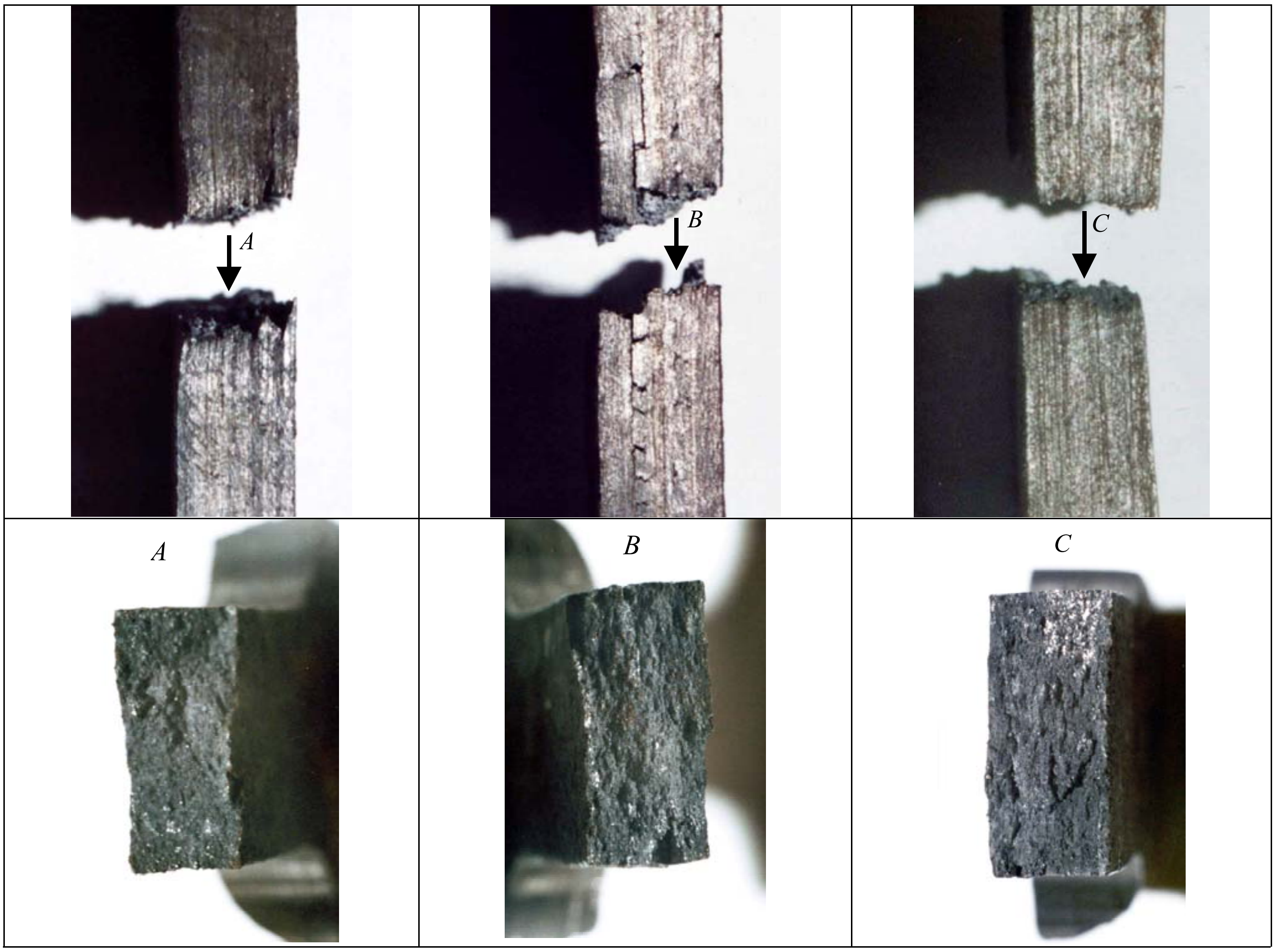
Generally, the disquisition of elastic-plastic mechanical properties of wrought iron is rather problematic because of the inconstancy of structural and physical parameters.

3.3. Notch impact tests

The impact conditions are usually examined under the tensile stress conditions existing on the tension side of the bending specimens. The size of a specimen is important, since the increased size tends to decrease in critical energy per unit area of the fracture [4].

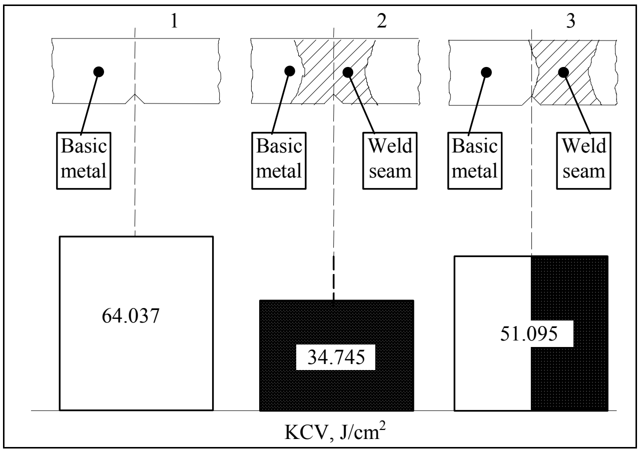
The testing scheme for impact strength *KCV* and the fracture phenomena of the welded wrought iron specimens are represented in Fig. 4.

Specimen No.1 demonstrates the plastic character of the impact fracture and the highest value of the impact strength. The brittle fracture was revealed in specimen No.2, where the notch was centered in the weld seam. The V-notch situated in the interface area of the weld seam shows the intermediate values of impact strength ca 51 J/cm^2 (Fig. 4 a, specimen No.3). The examples of the impact fracture of the specimens of the Šilutė wrought iron (*KCV* = 64 J/cm^2) and of steel St.3 (*KCV* = 90 J/cm^2) are shown in Figure 5. Wrought iron demonstrates the special character (rhombus) of the impact fracture, affected undaubtedly by the slag inclusions.

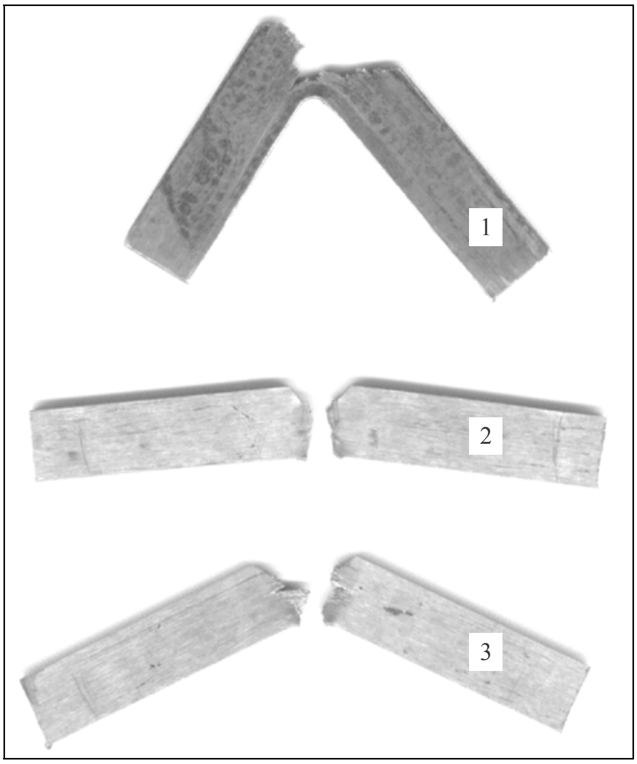


Specimen No.1 Specimen No.2 Specimen No.3

Fig. 3. Static fracture of the Šilutė bridge specimens, magnification ×2

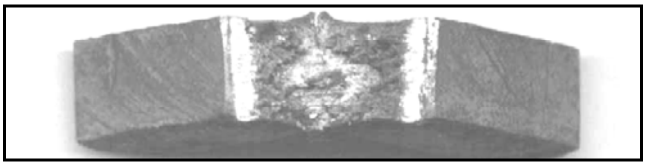


a



b

Fig. 4. The testing schemes of impact strength: a – values of impact strength and the V-notch positions on the specimen; b – specimens after impact fracture; 1 – a specimen without the weld seam; 2 – a specimen with the weld seam and centered V-notch; 3 – a specimen with the V-notch in the interface area



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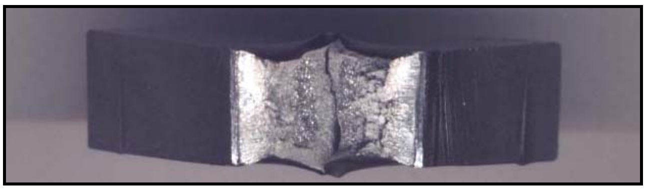

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Fig. 5. Comparison of the specimens of impact fracture: a – wrought iron; b – steel St.3 (GOST 380-88)

4. CONCLUSIONS

1. The microstructure and chemical composition of the analysed specimens indicate them to be of typical wrought iron containing ca 2.5 % of the refining slag inclusions. The elongated shape of inclusions and relatively fine grains of a metallic matrix are affected by rolling and by proper recrystallization process.
2. The mechanical characteristics of wrought iron are appreciably influenced by the slag inclusions rather evenly distributed along a metallic matrix. Solid solution of phosphorus in ferrite also confers a strengthening effect on soft metallic matrix. Therefore the mechanical properties of examined wrought iron specimens cut out of the Šilutė bridge are pretty high, corresponding to the respective properties of the modern mild steels containing 0.1…0.15 % of carbon.
3. The assay on the arc welding of the Šilutė bridge specimens demonstrates good enough arc weldability of wrought iron. The notch impact tests, however, have indicated significantly lower values of impact strength of the weld seam (ca 34.7 J/cm^2) as compared with the certification data of electrode material (90 J/cm^2). Thus, the necessity to establish technological and mechanical characteristics of the arc welding of wrought iron requires further investigations.

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