Towards a non-destructive methodology to distinguish wrought iron from mild steel in 19th century structures

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Abstract

During the 19th century various new construction materials became available in a short time. This paper deals with the quest for a methodology to differentiate wrought iron from mild steel by using a combination of several onsite non-destructive testing instruments. A mobile Vickers hardness tester and an optical microscope were used to determine the hardness and analyze the microstructure after onsite polishing and nital etching of historic wrought iron and mild steel structures. The historic specimens were also tested in a destructive way (tensile test) to obtain values for the mechanical properties and relate these values to the NDT results. Although the hardness measurements showed very large scatter, a trend in the measurements could be defined: large variations in local hardness measurements are a clear indication of wrought iron, which can be explained by the inhomogeneous micro-structure. Low variation in hardness is typical for mild steel. In the latter case a conversion from hardness to tensile strength is possible. The obtained dataset, coming from different Belgian structures dating from 1895 to 1905, is compared to datasets originating from the UK and US in order to position the Belgian historical iron alloys within a larger international context.
Keywords: hardness test, wrought iron, mild steel, metallography, NDT.

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1 Introduction

During the second half of the 19th century various new construction materials became available in a short time. Engineers first applied cast iron to create slender structures, mostly in compression. Around 1860 they turned to wrought iron and from 1880 onwards to mild steel.

Where cast iron can easily be distinguished with the naked eye due to its form and surface structure, the difference between sound wrought iron and mild steel is not visible as the same techniques were used to roll sections into their final form. However, when focusing on the production process, the microstructure and the mechanical properties, wrought iron and mild steel are clearly two different products and one should take this difference into account when renovating structures.

Previous research [1] has indicated that using the terminology 'wrought iron' and 'mild steel' is confusing. In this paper we will talk about *weld iron/steel* when we refer to the inhomogeneous fibrous product that has been produced by the puddling, the reverberatory, the dansk or the rotary furnace. We will talk about *ingot iron/steel* when we refer to the homogeneous product that comes out of the Bessemer/Siemens Martin or Thomas converter.

1.1 Weld Iron/steel

Weld iron/steel has a layered structure. It is composed of thin layers of almost pure iron with thin threads of slag in between. The large slag elements, sometimes visible with the naked eye, are squeezed into tubes due to the rolling process. The orientation of the slag in weld iron/steel causes different characteristics in the transverse and longitudinal direction. The strength in the longitudinal direction of a bar is on average 7 to 10 percent higher than in the transverse [2, 3]. Analysis of historical test data and modern tests on historical samples show that the variation of mechanical properties (tensile strength, ductility, toughness, elongation) is quite high between structural sections and even within a single section [4, 5]. Weld iron/steel can be weak or strong (tensile strength 140 – 530 MPa), brittle or ductile (elongation between 1 and 36 percent).

1.2 Ingot iron/steel

Ingot iron/steel has been heated to a liquid form during the manufacturing process. It has undergone fusion leading to a homogeneous structure. Ingot iron/steel has a more consistent microstructure then weld iron/steel. The impurities or inclusions in the steel are much smaller and more distributed.

2 Test set-up

In general, when renovating a metal structure, a sample is taken from the structure and tested in a destructive way. As it is not always possible or desirable

to remove samples from a structure, we investigate what kind of information non-destructive tests can deliver. Nowadays onsite chemical analysis, hardness tests, and metallography are possible. This paper examines the use of a non-destructive hardness tester as well as metallographic analysis.

As the results obtained by non-destructive testing have to be evaluated with the real material characteristics, the samples were also tested in a destructive way. Five samples from structural elements (I- and U sections, plates) were recuperated from renovated Belgian buildings dating from 1895-1905.

2.1 Destructive testing

Tensile testing coupons were machined from the structural elements, according to EN10 002-1, to determine the strength and ductility.

Table 1: Mean values of the Young's modulus, yield tress, ultimate tensile strength, strain, area reduction and Poisson's ratio for five historic samples determined by tensile tests.

Samples	Young modulus [GPa]	Yield stress [MPa]	Ultimate tensile strength [MPa]	Strain [%]	Area reduction [%]	Poisson's ratio [-]
Ingot-procedure:						
1/1895/I	197	278	391	31	61	-0,28
2/1895/U	200	334	452	24	47	-0,26
3/1905/I	199	353	469	27	57	-0,27
Weld-procedure:						
4/1903/-	184	306	380	20	29	-0,29
5/1903/-	190	305	371	17	26	-0,29

Remark: '2/1895/U' refers to sample 2 cut out a U-section from a 1895 building

2.2 Metallography

To study the microstructure's grain size and inclusions, the samples were mechanically polished and nital etched in lab conditions, as preparation for optical microscopy analysis. To compare this mechanical lab-etching metallographic procedure to the onsite metallographic sample preparation, onsite conditions were also imitated in the laboratory. The surfaces of the metal samples were polished manually by gradually diminishing the grade of wet (silicon carbide) sandpaper from P#500, P#800, P#1200, P#2400 to P#4000 (see Figure 1). Subsequently a small area of the polished sample is chemically etched by dribbling nital on the cleaned surface for 5 minutes.

The same optical microscope was used to study the lab as well as the onsite samples, but magnifications were limited to values feasible for onsite analysis. Magnifications of x50, x100 and x200 were applied when analysing the etched samples. The pictures from the lab etched samples are sharp. The homogeneous structure of sample 3 refers clearly to the ingot-procedure, whereas the large

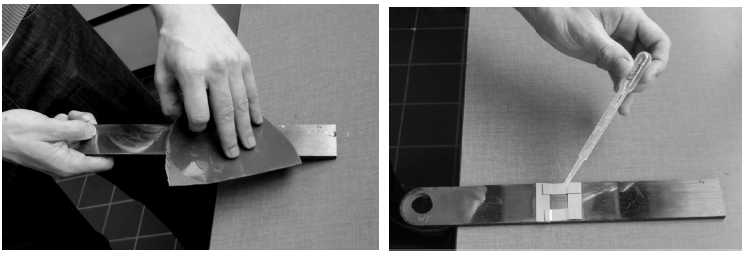

Figure 1: Manual polishing of the metal sample (left). Manual nital etching of a defined area on the metal sample (right).

inclusions, typically elongated in one direction, and the layered structure of sample 4 refer to the weld-procedure.

Although the pictures of the onsite etched samples are less clear due to higher surface roughness of the manual polishing, this trend is visible on a scale of 200x as well as on a scale of 50x, which is possible to apply onsite.

As a consequence, onsite polishing, etching and metallography can be used to determine whether steel structural elements were produced according to the weld- or ingot-procedure. The metallography does not give any information about the strength or ductility of the sample.

2.3 Portable hardness tester

Hardness tests are extensively used in quality control. The measurements are fast and easy to perform, which make them attractive to use during a renovation process. For modern steel there is a reasonably accurate correlation between hardness and tensile strength and conversion tables available, which are based on numerous tests [6]. The validity of this correlation for historic weld and ingot iron/steel structures remains to be determined.

Different instruments can be used to measure the hardness. As the microstructure of the historical metal is heterogeneous, the diameter of the indentation will influence the measurement. The larger the size of the indenter, the more average the measured hardness will be, as it is measured on a surface area containing various microstructural inclusions. Conversely, when smaller indentations are used, like with a Vickers test, more local hardness information is obtained, which will reveal influences of local surface differences in microstructure and enables to reveal a hardness gradient.

The hardness of the five polished samples was determined using three static hardness testers:

- Rockwell hardness tester, scale B, 500N load, indentation 1/16 inch steel ball,
- Vickers hardness tester ‘Struers Duramin’, load of 20N during 10s,
- Portable MIC 10 Vickers hardness tester, with 205-A indenter (50N).

On every historic sample 10 hardness measurements were taken for each hardness test. The loads applied on the metal samples give indentations of about

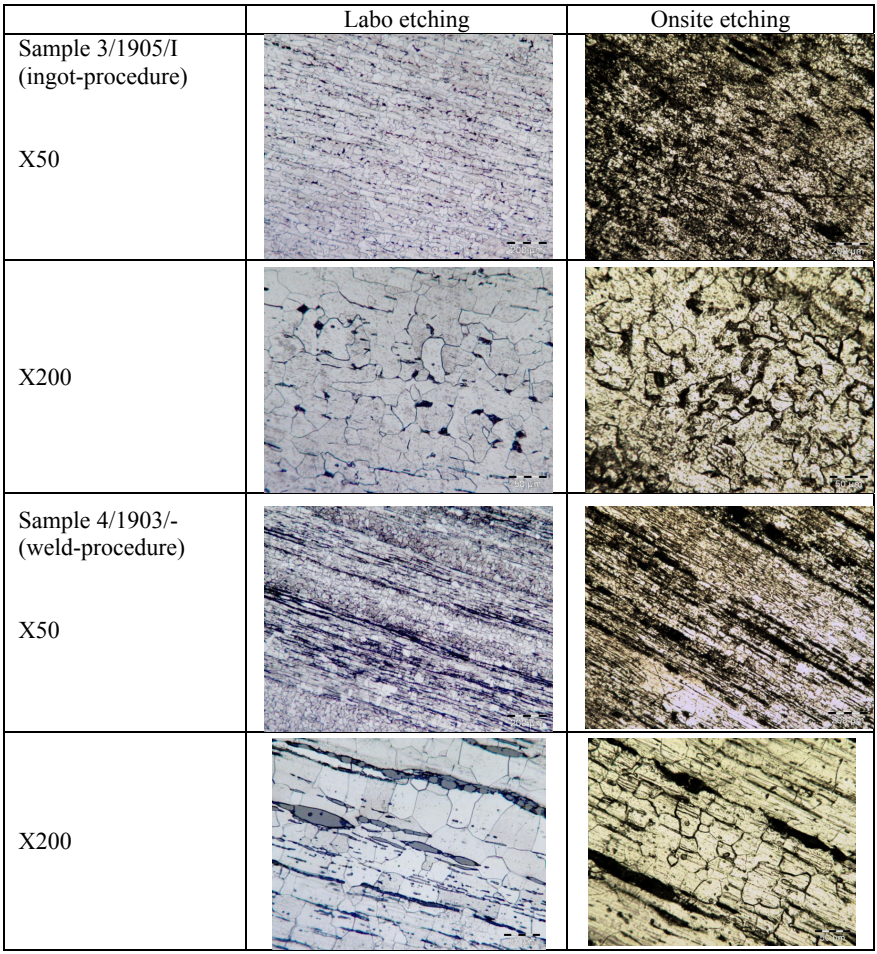

Figure 2: Comparison between the pictures of the metallography (magnification x50 and x200) from the mechanically (left) and 'onsite' (right) polished samples for the ingot (up) and weld (down) procedure.

150µm with the Vickers tester, 270µm with the portable Vickers tester and 950µm with the Rockwell tester. Figure 3 shows the proportion of the indentation compared to the slag (50µm).

Table 2, which gives the mean values and the standard deviation of the hardness measurements, illustrates that the standard deviation is larger for the samples fabricated according to the weld-procedure. Hence, we can state that large deviations of the hardness measurements indicate a heterogeneous structure and point to the weld-procedure, whereas small variations point to the ingot-procedure.

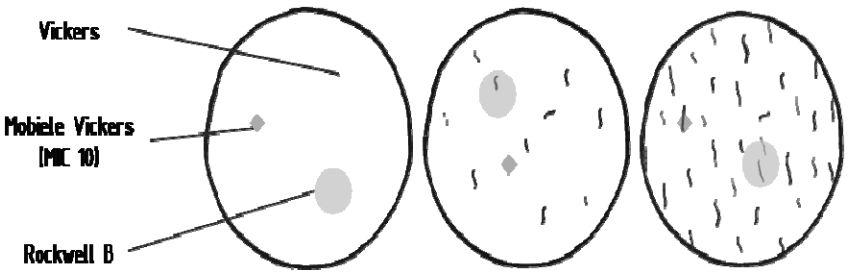

Figure 3: Schematic of the influence of the indentation area of the hardness testers (left) on the analysed surface of historic ingot iron/steel (middle) and weld iron/steel (right) with different microstructures.

Table 2: Hardness of the five historic metal samples tested with (portable) Vickers and Rockwell hardness testers.

Samples	Vickers HV 20N		Portable Vickers HV 50N		Rockwell B HRB 500N	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Ingot-procedure						
1/1895/I	127	4	120	9	62	2
2/1895/U	151	8	147	14	74	4
3/1905/I	153	3	129	12	74	1
Weld-procedure						
4/1903/-	174	20	210	53	73	7
5/1903/-	124	11	120	44	63	6

The prediction of the ultimate tensile strength for the weld procedure shows larger variations. Other researchers were confronted with the same conclusions [4, 5, 8]. Bowman and Piskorowski [5] collected historical data sets of tensile load tests on wrought iron. Figure 5 plots the ultimate tensile strength of more than 1500 wrought iron bars, plates and angle iron tested by the English scientist Kirkaldy and the American Beardslee together with the Belgian specimens data.

To convert the hardness values into ultimate tensile strength, we used *Uconeer* [7], which is a program based on an extensive set of experiments on modern carbon steel and steel alloys, as conversion tables for historic steel do not exist (yet).

Table 3 indicates that the ultimate tensile strength could be predicted from the hardness values within a margin of 11% for ingot samples. This might not be accurate enough for a structural calculation, but will enable engineers to determine whether the steel qualities of two structural elements are comparable.

Figures 4 and 5 show high variation of the tensile strength and percent elongation for historic wrought iron. The Belgian specimen show higher tensile strength but lower ductility, which indicates once again the importance to determine the mechanical properties when dealing with weld iron/steel.

Table 3: Conversion of hardness to ultimate tensile strength (UTS) and correlation with tensile test.

Samples	Tensile test	UTS converted from hardness test					
		Vickers HV 20N		Portable Vickers HV 50N		Rockwell B HRB 500N	
	UTS [MPa]	UTS_{HV} [MPa]	Δ [%]	UTS_{HV} [MPa]	Δ [%]	UTS_{RB} [MPa]	Δ [%]
Ingot-procedure							
1/1895/I	391	418	7	396	1	374	-5
2/1895/U	452	493	8	480	6	441	-3
3/1905/I	469	499	6	424	-11	440	-7
Weld-procedure							
4/1903/-	380	565	32	680	44	431	379
5/1903/-	371	408	9	396	6	12	2

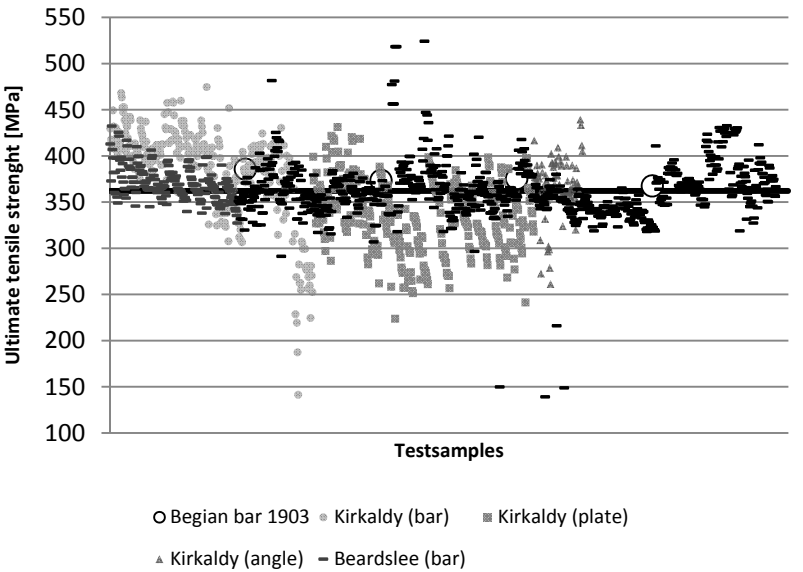

Figure 4: Ultimate tensile strength of the Belgian coupons against the historic dataset on wrought iron by Kirkaldy and Beardslee [5].

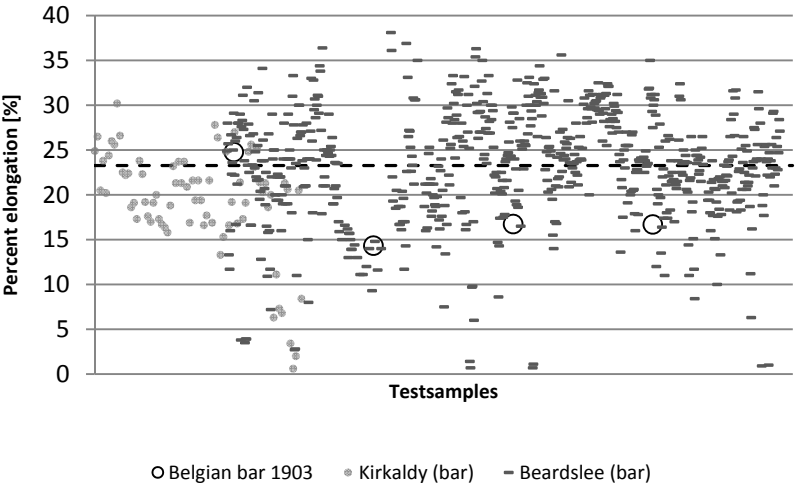

Figure 5: Percent elongation of the Belgian coupons against the historic dataset on wrought iron by Kirkaldy and Beardslee [5].

3 Conclusion

Metallography and a transportable Vickers hardness tester were used to determine the kind of metal in historic metal structures as well as to predict the ultimate tensile strength. Comparison with the test results from the destructive tensile coupons, onsite metallography as well as an onsite hardness tester can be used to determine whether the structure is of ingot or weld iron/steel. Hardness tests can be carried out to check whether the different components of a composed structural element are built up with the same material and the same quality.

If the structure is made out of ingot iron/steel, then the lower and upper boundary of the ultimate tensile strength can be predicted using the standard conversion tables. That way, structural engineers have a first indication for their structural analysis. They have a 'safe' value and know the upper limit of the steel quality. If the structural element needs to be stronger than this upper limit, additional destructive tests are of no use. If the structural element is weld iron/steel, additional testing is needed as the material characteristics can fluctuate between wide limits.

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