Modelling of bloomery processes in a medieval Russian furnace

Modelování procesu přímé výroby železa v ruské středověké peci

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A fully preserved 14th-century AD bloomery furnace was excavated in 2014 on the settlement of Kolesovka-4 (Russia, Tula district). This extraordinary find has been taken as a model for experimental work. The iron ore used came from the Loknya River, a metallurgical conglomerate used came from the archaeological site of Staraya Ryazan. The most successful result was achieved by using the conglomerate from Staraya Ryazan – three pieces of blooms were made, weighing about 1 kg, and consisting of soft iron and a large number of very coarse slag inclusions. These show a similar trace-element composition as the medieval bloom coming from the same site. Experiments conducted have shown that the bloomery furnace uncovered at the Kolesovka-4 settlement is a rational pyrotechnological construction, allowing for a large number of smelting cycles.

bloomery process – modelling – furnace – metallography

V roce 2014 byla na sídlišti Kolesovka-4 (Rusko, okres Tula) odkryta plně zachovaná železářská pec ze 14. stol. n. l. Tento mimořádný nález posloužil jako model pro experimentální práce. Použitá železná ruda pochází z řeky Loknja, použitý metalurgický konglomerát pak z archeologické lokality Stará Rjazaň. Nejlepšího výsledku bylo dosaženo použitím konglomerátu ze Staré Rjazani – získány byly tři kusy železné houby vážící asi 1 kg a sestávající z měkkého železa a velkého množství velmi hrubých struskových vměstků. Ty vykazují podobné složení stopových prvků jako železná houba pocházející z té samé lokality. Provedené pokusy ukázaly, že redukční pec odkrytá na sídlišti Kolesovka-4 je racionální pyrotechnologické zařízení umožňující řadu výrobních cyklů.

přímá výroba železa – modelování – pec – metalografie

One of the most challenging issues when modelling a bloomery process is defining the type and size of a bloomery furnace. Archaeological remains of pyrotechnological structures, in the vast majority of cases, survive only fragmentarily, and information on numerous important features, such as construction of a furnace shaft and its height, position and number of tuyeres etc., are lacking. From this perspective an outstanding discovery was made by archaeologists of the museum 'Kulikovo Pole', who uncovered a fully preserved bloomery furnace at the 12th–14th century AD settlement of Kolesovka-4 (Tula region, Russia).

The furnace is a self-supporting, rounded construction with a vertical 75 cm high shaft (*fig. 1*).[1] Thickness of wall: 12 cm; diameter below: 46 cm; diameter at the top: 16 cm. A hole situated in its lower part was closed during smelting by a panel with an opening for the tuyere (through which air was blown into the furnace); when the smelting was finished, the hole was opened again to pull out the bloom. In front of the tuyere panel there was a small clay platform edged with short boards on the sides. The furnace was built on the

[1] I thank dr. Andrey Naumov for permition to use unpublished materials.

Fig. 1. The medieval furnace from Kolesovka-4 archaeological site (Tula region). Photo by A. Naumov.
Obr. 1. Středověká pec z archeologické lokality Kolesovka-4 (oblast Tula).

clay base, which was a little bit wider than the lower part of the furnace. The base of the furnace on the perimeter had a layer of limestone rock particles. The outer surface of the furnace was covered with clay.

The replica of this furnace was built in Ryazan[2] to conduct experiments on modelling of medieval metallurgic processes (*fig. 2*). The construction of the bloomery (excluding preparation work) took about one hour. After drying, which took a week, the furnace was fired with dry pine firewood.

In total, eight smelting experiments were performed using the furnace constructed in 2015–2016. It should be mentioned that the construction withstood well the wintertime. After a long (about ten months) pause only an additional daub of the outer and inner surfaces was needed.

Tuyeres made of local clay (with addition of sand or charcoal) were used for all the experiments conducted. Length of the tuyeres was 20–25 cm; inner diameter was 2–2.5 cm. The tuyeres were put into the furnace at an angle of about 30 degrees. A single bellow, provided continuous air supply, (*fig. 3*) was used for air blasting (speed of air flow was 260 l/min).

[2] The furnace was built and experiments were carried out with the help of Mikhail Ratkin (Ltd Arta, Ryazan).

Fig. 2. The experimental model of the medieval Russian furnace. Photos in *figs. 2–4* by V. Zavyalov.
Obr. 2. Experimentální model ruské středověké pece.

The process started with 1 to 1.5 hour pre-heating of the furnace using dry pine firewood. The temperature on the throat of the shaft reached up to 550–600 °C. Afterwards, the furnace was charged up with charcoal and a powerful draft was provided.

Metallurgical raw materials used for the experiments were collected on the archaeological sites. The most successful result was obtained using a slag-iron conglomerate from Staraya Ryazan (Старая Рязань, archaeological site, town destroyed by Mongols in 1237). However, the success is connected mainly with the fact that the correct temperature regime (achieved by powerful draft before charging first iron ore, moderate draft in the consequent process of ore charging and the continuation of the powerful draft before the end of the process) was successfully maintained during the experiment.

Before the smelting, ore was roasted on a bonfire. An ore layer, which was cross-covered by poles, was lain on the row of wooden poles. The next ore layer was spread and then from four to five more layers. The ore roasting lasted 1–1.5 hours (until the complete burning out of a wood). Finally the ore lost 7–10 % of its initial weight.

The proportion of ore to charcoal in a charge was from 1 : 1 to 1.5 : 1 (not counting the charcoal charged into the furnace before the smelting process). The proportion of the iron conglomerate to charcoal was the same. The charge was added into the furnace in portions of 2–3 kg (first – the ore, then the charcoal) after the subsidence of the previous portion. Time intervals between charging were from 5 to 15 minutes. It is worthy to note that in successful experiments these intervals were minimal. Therefore it took 1.5 hours to charge 10 kg of ore and the process itself (from charging the first portion) took 2–2.5 hours.

As mentioned above, the most successful result was achieved by charging the iron conglomerate from Staraya Ryazan. The conglomerate is a mechanical mixture of a not completely slagging gangue, iron oxide (FeO), magnetite (Fe_3O_4) and some small fragments

Fig. 3. The experimental furnace in operation.
Obr. 3. Experimentální pec za provozu.

of reduced iron. During the experiment 7 kg of the conglomerate was used and three pieces of bloomery iron weighing 1 kg (altogether) were made. Metallographic examination of one of these pieces revealed a structure of ferrite with disproportionate grain size (2–5 GOST[3]) and with a number of large slag inclusions. Microhardness of the ferrite is 170–181 HV0.1.

A concentration of the conglomerate was found in the surface layer on the plain between Northern Promontory and Northern settlement in Staraya Ryazan. While studying the conglomerate, a bloom, which had a shape of irregular hemisphere, stretched a bit in a plan was noticed. The size of the bloom is 13 × 10 × 4 cm and its weight is 0.83 kg. The bloom is covered with a slaggy layer, and the iron is concentrated in its lower part. There are a lot of pores and slag on the surface of the metal, the structure of which contains tempered martensite as determined by metallographic examination. Microhardness of the metal is 383–420 HV0.1. In order to determine the carbon content, the fragment was annealed by heating at 800 °C and by consequent slow cooling (the fragment was placed next to a hearth) to ambient temperature. Metallography of the annealed sample revealed ferritic and ferritic-pearlitic structure. Carbon content reaches up to 0.7 % in places. Microhardness of the ferrite is 110–128 HV0.1, and of the ferrite-pearlite 193–221 HV0.1.

A bloom discovered in Staraya Ryazan offered an opportunity to compare the element composition of the experimental samples with the archaeological material. Eighteen analyses have been carried out in total: one – ore from Istye, three – experimental bloomery iron, six – bloom from Staraya Ryazan, six – experimental conglomerate and two – archaeological conglomerate from Staraya Ryazan.

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[3] GOST 5639–82 (Russian state standard for grain size determination in steels and alloys).

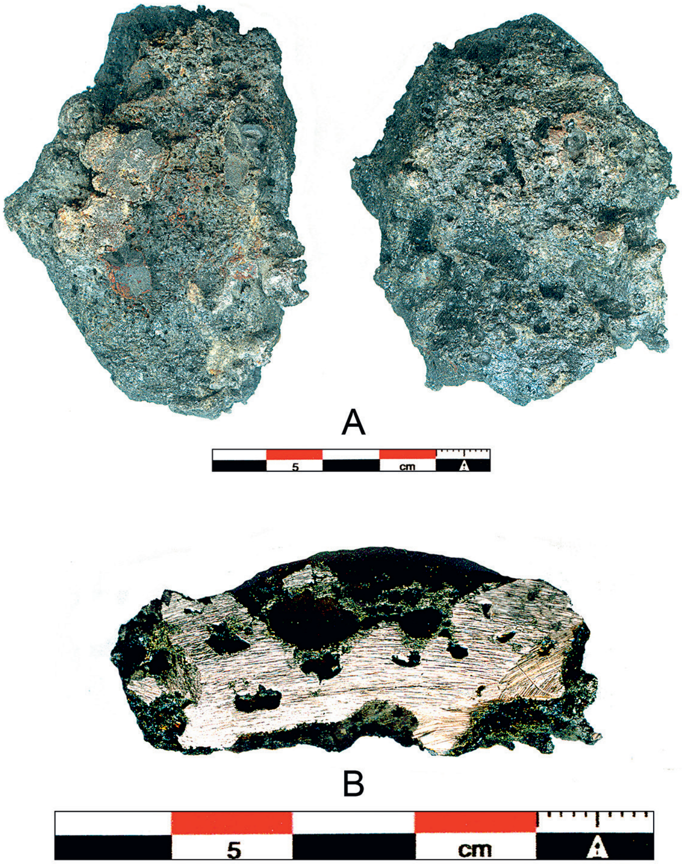

Fig. 4. A – bloomery iron made during the experiment; B – cross section of a sample from the bloom.
Obr. 4. A – železo vyrobené v rámci daného experimentu; B – průřez vzorku železné houby.

The archaeological slag-iron conglomerate from Staraya Ryazan differed in quite high concentration of iron oxide (53.5–60.8 %) with silica (8.1–12.1 %) and alumina (0.1–1.1 %) concentration. The conglomerate yielded within the experiment has 63.7–65.6 % of iron oxide, 34.1–38.2 % of silica and 11.2–15.5 % of alumina. Hence, in the experimental smelting more iron was needed for slagging the gangue in comparison with the medieval process. However, more gangue occurred in the experimental conglomerate.

An important factor of a successful bloomery process is the viscosity index of slag which shows the complete burrow removal from the charge (first of all, silica and alumina). According to Bachman's data, the viscosity index varies from 0.5 to 1.0 (*Bachman 1982*). The computation of the viscosity index for the mentioned samples showed that only one sample (13080) received in the experiment has this index close to the range given. In the metallographic analysis an even dark grey structure (fayalite) was discovered in the sample 13080 with a large amount of pores and separate round particles of white colour. So to say exactly this sample is actually a piece of slag. Still the rest of the fragments (experimental as well as archaeological) which showed the viscosity index significantly higher than 1 and did not have flow characteristics – in other words, they were conglomerates.

Sample	Ag	As	Mo	Cu	Ni	Fe	Mn	Al	S	P	Si	Mg
Ore from Istya				–		**46.4**	0.9	0.8	0.1	0.2	3.4	
Conglomerate	0.4	–	–	–	–	**38.5**	0.2	–	–	–	–	–
Conglomerate	–	–	–	–	–	**55.0**	0.2	7.4	0.2	0.1	18.1	–
Slag	–	–	–	–	–	**49.5**	0.2	5.9	0.2	–	15.9	–
Slag	–	–	–	–	–	**51.0**	0.2	8.2	0.2	–	17.8	2.2
Slag	–	–	–	–	–	**3.9**	0.1	17.8	–	–	39.8	–
Slag	–	–	–	–	–	**3.4**	–	15.6	–	–	48.7	0.7
Bloom exp.	–	–	0.1	–	–	**99.8**	–	–	–	–	–	–
Bloom exp.	–	0.1	0.1	0.1	0.3	**99.3**	–	–	–	–	–	–
Bloom exp.	–	–	–	0.2	0.9	**97.4**	0.7	–	–	–	–	–
Bloom St.Ryazan	–	–	–	–	–	**99.9**	0.1	–	–	–	–	–
Bloom St.Ryazan	–	–	–	0.1	0.1	**99.7**	–	–	0.1	–	–	–
Bloom St.Ryazan	–	–	–	0.1	0.3	**98.2**	0.5	–	–	–	–	–
Bloom St.Ryazan	–	–	–	0.1	0.3	**98.2**	0.4	–	–	–	–	–
Bloom St.Ryazan2	–	–	–	–	–	**100.0**	–	–	–	–	–	–
Bloom St.Ryazan2	–	–	–	0.1	0.2	**97.6**	0.1	1.0	0.4	0.2	–	–
Slag-aug2016	–	–	–	–	–	**55.7**	0.1	3.3	0.1	0.3	17.4	–
Slag-aug2016	–	–	–	–	–	**48.9**	0.1	1.6	0.2	0.2	16.8	–

Tab. 1. The element composition of materials analysed (in wt%; XRF spectroscopy).
Tab. 1. Prvkové složení analyzovaných materiálů (v hm%; XRF spektroskopie).

It is known that the result of the bloomery process was chemically 'pure' iron and the elements discovered during the experiment (excluding carbon, phosphorus and arsenic which form a solid solution with iron) enter the slag (the amount of which can reach 2–3 %) saturating bloomery iron (*Kolchin 1953*; *Zavyalov – Estrova 1987*). Considering the element composition of the metal from Staraya Ryazan and that of the experimental blooms, it should be mentioned that all elements detected were trace impurities which did not influence the metal characteristics. At the same time, similar concentration ratios of elements were observed in the experimental and archaeological blooms: in both cases the peaks are accounted for nickel and manganese, while contents of copper, arsenic, lead and titanium were close to zero (see *tab. 1*). The element composition of iron products from Staraya Ryazan and from the settlement of Istye-2 is similar.[4] In comparison, the element composition of iron products from Sarmatian sites was considered. As it can be seen from the chart in Sarmatian items the trace impurities of copper are significantly prevailing while the content of other elements is close to zero.

[4] The site of Istye-2 was a specialized metallurgical settlement providing Staraya Ryazan with iron (*Bulankin – Zavyalov – Ivanov 2012*).

The results of the experimental and analytical researches allow the following conclusions to be made:

1. The bloomery furnace uncovered at the settlement of Kolesovka-4 is a rational pyrotechnological construction allowing for a large number of smelting cycles.

2. Experimental works on extracting iron from slag-iron conglomerate showed that the conglomerate could be used by medieval bloomery smelters instead of iron ore. This conclusion proves the suggestion of A. Espelund on processing of production residuals (*Espelund 2005*).

3. The bloom received from the medieval slag-iron conglomerate had the content of trace impurities similar to the archaeological bloomery iron found at the same site.

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