

Mechanical fasteners used in historical Siberian shipbuilding: perspectives for metallurgical analysis*

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Abstract. Recent discoveries of shipwrecked vessels in the northern reaches of the river Yenisei led to a number of questions concerning the history of shipbuilding in Siberia and the technical features of the first vessels of the industrial era to navigate the Northern Sea Route and the Yenisei. One of these questions addresses the features of mechanical fasteners used in the construction of the Siberian vessels. The answer to this question may provide information on how the first vessels, constructed in Siberia during the 1870's, were able to sail the high seas of the Arctic Ocean and reach European ports. In this paper, we provide a description of iron mechanical fasteners obtained from one shipwrecked vessel and discuss on the perspectives of a metallurgical analysis

1. Introduction

Recent expeditions to the Siberian Arctic, both scientific and amateur, have revealed a number of unidentified shipwrecked vessels [1]. Unfortunately, the problem of historical shipbuilding in Siberia has yet been properly addressed in research literature. Samples of mechanical fasteners from the discovered ships, the majority of which are barges, may shed light upon this issue.

This paper addresses the problem of historical shipbuilding in Siberia in the latter half of the nineteenth century and the early half of the twentieth century, specifically focusing on the mechanical fasteners used for the construction of these vessels. A short history of shipbuilding in Siberia during Russia's era of industrial development is given, the field research of the historical expedition, which collected and examined many of the samples of mechanical fasteners is reviewed upon. The paper then proceeds to discussing the prospects of conducting a metallurgical analysis of the collected samples, describing the procedure of such an inquiry and stating the predictions.

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Due to space limitations, the authors shall focus, primarily on shipbuilding on the Yenisei. This river was more important to navigation on the western leg of the Northern Sea Route as it could be easily accessed by large oceangoing vessels, unlike the neighboring Ob'. This fact stimulated the development of marine shipbuilding on the Yenisei. However, naval architecture was similar throughout all of Siberia, as it will be shown in this paper, making shipbuilding on the Yenisei a potent example for further research.

2. Shipbuilding in Siberia. Results of the 2016 expedition

Historical literature offers very little information on the subject of Siberian shipbuilding. The topic is briefly considered in a number of studies on the history of the Northern Sea Route and the development of navigation on the great Siberian rivers, the Ob', the Yenisei, and the Lena, however, to our knowledge, no inquiry has yet been made into the technical features of the vessels constructed locally. Even the more prominent vessels, which made their way into the annals of the history of the Northern Sea Route, the clipper-boat *Severnoe siianie* (Aurora Borealis) and the schooner *Utreniaia zaria* (Morning Dawn), continue to remain unknown in terms of their technical features. An essay by E.N. Vladimirov, published in 1940, continues to remain the only potent publication on the technical characteristics of these two vessels. Vladimirov specifies that the first vessel was 90 feet long, 14 feet wide, and 8 feet high [2]. No further information is provided and the author fails to cite any source. The second vessel is described on the basis of a note, written by the shipwright of both vessels, the Heligolander Petr [Peter] Boiling. The schooner is described as having a length of 56 feet, a width of 14 feet, and a height of 7 feet. The displacement is 50 tons. The vessel was built from a variety of woods: larch was used for the bottom and hull draft; pine and fir were used for the rest of the ship [2]. The skipper of both vessels provides some additional information on the features of the *Severnoe siianie*, specifically its tonnage – approximately 100 tons, and some details on the rigging [3].

The vessel was lost with most of her crew during the winter and spring on 1876–1877. In 2016 an expedition was launched by Reshetnev Siberian State Aerospace University (SibSAU) and the Russian Geographical Society to find the wreck of the 140-year old ship in the delta of the Yenisei. A wreck was found on the island Bol'shoi Brekhovskii in the Brekhovskie ostrova archipelago (wreck A). As it was determined that it was on this island that the crew of the lost vessel had wintered, it was proposed, on site, that the wreckage could be the clipper-boat *Severnoe siianie*. The dimensions of the wreck matched the description, given in Vladimirov's essay. After a press conference with the expedition team, Russian and international mass media reported the find to be the nineteenth-century vessel.

Further investigation showed that the vessel was actually much younger than the proposed ship. This immediately posed a problem as there is very little evidence on both the subject of shipbuilding in Siberia and wrecked vessels in the Yenisei delta. The expedition found another vessel at the settlement of Kalaul (wreck B). From its size and preserved features, it was determined that this was a wrecked barge or lighter. Some features of this vessel's design, particularly the mechanical fasteners used, were very similar to the ship found of the Bol'shoi Brekhovskii ostrov.

It has been suggested that both vessels were built between the 1930's and 1950's. From archival materials we know that the majority of barges and lighters for needs of the Northern Sea Route have been built at Krasnoyarsk and Pridivinsk [3; L. 153]. By the mid-1930's it was becoming increasingly evident that it was necessary to begin vessel production at Igarka [5, L. 112]. Another facility on the Yenisei that had its fleet of barges was the port of Dudinka. By 1939, Dudinka had 28 barges with a gross tonnage of 21,200 tons (750 tons of

tonnage for each barge) [6, L. 106].

It is known from both archival sources and historical literature that rudimentary shipbuilding existed on the Yenisei beginning from the seventeenth century. However, vessels that could operate during continuous periods in the mouths of the great Siberian rivers and in the seas of the Arctic Ocean were built on a large scale beginning only from the late 1800's. This is especially true for the Yenisei, where river navigation was less intense than on the neighboring Ob'. At the same time, the experience of both traditional Russian shipbuilding and the construction of European-style ships for the Great Northern Expedition (1733–1743), which was an exceptional event, had little impact on the further development of local river shipbuilding. Considering that navigation in the Kara Sea to the mouths of the Ob' and Yenisei was first performed only in the 1870's, it is obvious that there was no naval engineering until this date. The slow but steady progress in the development of the western leg of the Northern Sea Route during the late 1800's and early 1900's advanced local shipbuilding, particularly the construction of barges and lighters. However, the remoteness of the first Siberian wharves made them extremely difficult to supply with industrial materials, primarily, sheet metal, iron structural elements, and mechanical fasteners. This made wood the material of choice for shipbuilding in Siberia until the 1950's. However the abundance of wood could not compensate the need for metal fasteners, which either had to be delivered as completely manufactured items, or as semi-finished products or raw material that would be processed locally.

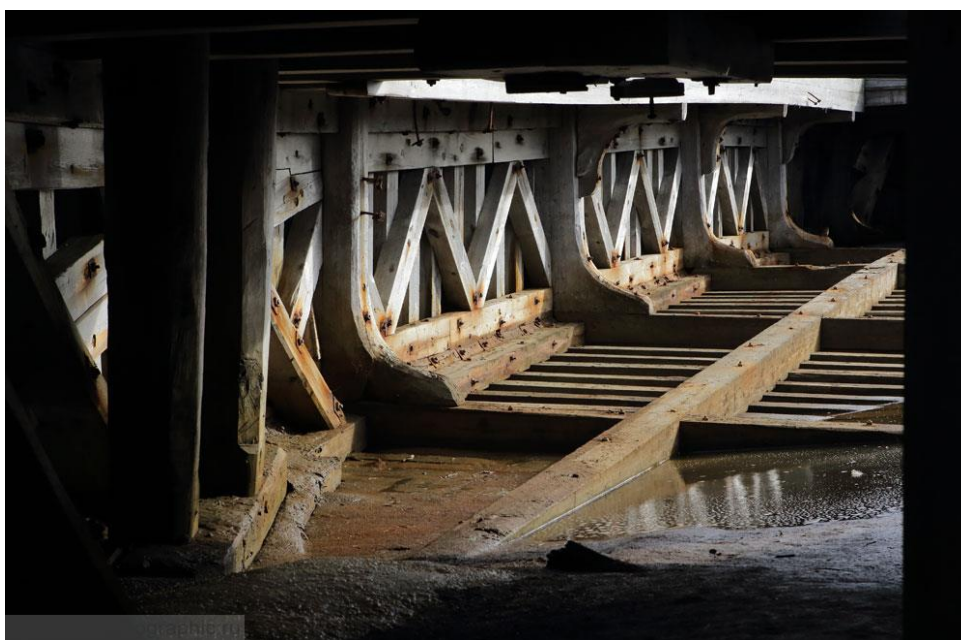


Figure 1. The structure of a barge hold (cargo box) as seen in a grounded barge wreck in the Laptev Sea (c. 1930's–1950's). Image from the 2014 expedition of Sergei Karpukhin (accessed <http://karpukhins.livejournal.com/181715.html>) (printed with permission of author)

Another problem is the dating of objects and structures that are between 150 and 80 years old. Typically, this problem does not occur as there is enough documental evidence reporting on the date a concrete object was built or lost. However there are still many cases when it is

extremely difficult for the researcher to find the necessary historical records. Over the last century and a half many documents have been lost or disposed of as not ‘having historical value’. Not being able to find reference in archives to the construction or destruction of a structure or object, researches turn to the local testimony. Very often, however, the locals are simply not aware that there is a historical site in the area, do not know its history, or provide inaccurate or exaggerated information on the object or site. Thus, such information can only be used if it is cross-examined with more reliable materials.

An example to illustrate the aforementioned point has been recorded during the 2016 expedition. The team was working on the river Sal’naia kur’ia, a tributary of the Yenisei, searching for the British steam-schooner *Thames*, which sank there in 1878. The locals confirmed that there was a wreckage of a vessel on the bottom of this river; however they were surprised to learn that this was a nineteenth century vessel, supposing that it was an ordinary motor boat (Russ. – *kater*) [7].

3. Types of mechanical fasteners used in Siberia shipbuilding

The 2016 expedition documented and photographed mechanical fasteners from both vessels found. Three samples of wrought iron nails (spikes) were retrieved from wreck A to conduct a laboratory investigation of its properties. In this section we shall review on the types of mechanical fasteners used in the construction of these two vessels and on the properties of wrought iron.

An intense study of the properties of iron fasteners (rivets) is given in [8]. Hooper et al. gives a definition of wrought iron as a commercially pure iron (less than 0.02 wt% C) with slag content of 1–2 wt% [8]. The puddler process was the chief production method of wrought iron during the late nineteenth and early twentieth century. Wrought iron would be the most available material for the construction of mechanical fasteners in Siberia until the industrialization of the 1930’s.

Table 1. Assortment of mechanical fasteners found on the two vessels

Type	Dimensions	Description
Nails (spikes)	Type A: $l = 25$ cm, $w = 0.8$ cm (at head)	Found in great number on wreck A. Used for attaching deck planks to the transverse beams of the frame. All collected samples are deformed (bent).
	Type B: $l = 35$ cm, $w = 1$ cm (at head)	Found in great numbers on both vessels. Used for attaching hull planks to the frame of the vessel. Many fasteners remain intact, holding outer hull planks to frame elements.
Bolts	$l = 9 - 40$ cm, $\varnothing 1.2$ cm	Most bolts are square-headed, singular hexagonal-headed bolts can be found. Bolts were the essential fastener for building the vessel’s frame. The deformation of the bolts is clearly visible. Found on both vessels.

Nuts	w = 3–4 cm	The prevailing type of nut is square. Singular hexagonal nuts can also be found. Little signs of strain can be seen. Found on both vessels.
Washers	w = 2–4 cm	All washers are either square or rectangular. Found on both vessels.
Threaded rods	l = 2–4 m, \varnothing 1.2 cm	Their function is not clear. Found only on wreck A.
Turnbuckles	l = 40–60 cm	Turnbuckles were used to connect two threaded rods and to create tension. As with the threaded rods, their function is not clear. Found only on wreck A.

An investigation into the types of mechanical fasteners provided clues on the construction date of the two vessels. The initial supposition that wreck A was the clipper-boat *Sevenoe siianie* proved to be erroneous. Besides the dimensions of the discovered wreck matching the ones of the nineteenth century vessel, it was considered that hand-wrought-iron nails (spikes) could not be used in the construction of vessels, produced after the 1800's. An inquiry into the history of nail production and their usage emphasizes on using nails to date old buildings; with the introduction of machine-cut nails in the late eighteenth and early nineteenth centuries, and wire nails, which became the dominant nail type beginning from the 1890's [9]. The nails, recovered from the first vessels (3 specimens), are of Type A (2 specimens (Figs. 2–3)) and of Type B (1 specimen (Fig. 3)). They are hand-wrought, being square in cross-section. The heads are produced by a heading tool. The head diameters vary from 4 to 4.5 cm.

As seen from the images of the wreck, nails were the most distributed mechanical fastener used to construct these vessels. Their implementation ranged from securing the bottom planks of the below waterline hull to the floor beams, securing the hull planks to the ribs, and fastening the deck planks to the deck beams. The use of such crude nails in Siberian shipbuilding lasted deep into the twentieth century. Apparently, industrial production of such large nails lagged behind the growing demand for them as the shipping on the Northern Sea Route became ever more intense. Local nail production, however obsolete, provided a temporary solution to the problem. However, in the 1930's it was also incapable of coping with the demands for the construction of new vessels and the maintenance of existing ones as seen from archival materials [5, L. 60 verso].



Figure 2. Nails from overturned deck planks. Signs of deformation caused by bending and torque are visible



Figure 3. Three nails taken from the first wreck as specimens for metallurgical analysis. Top – Type B; bottom (2) – Type A. All specimens were bent. The first nail was bent deliberately for additional structural strength; the second specimen demonstrates deformation caused by torque (apparently the wooden member was twisted around the axis of the nail)

Bolts, as seen from Table 1, played a critical role in the assembly of the ship frame (Figs. 4–5). The vessels, both of which were large river barges were flat-bottomed, which, according to structural mechanics, requires a stronger frame than curved or angular bottoms. The members of the frames of both vessels consist of ribs (15 cm thick), deck beams (not preserved), cross-members (diagonal beams), which provided extra support for the ribs, and floor beams. All of these structural elements were held together by bolts. The washers that were fitted on the bolts and provided load distribution over the surface of the wooden members were all crudely made from lengths of iron or steel strips and cut to size. The majority of nuts were also crudely made, being square and even rectangular, although separate hexagonal nuts can still be seen on the wreck; these, most likely, were imported from the industrial centers of European Russia.



Figure 4. Two bolts, square washer, and square nut with scale marker. These two samples were bent



Figure 5. Demonstrates the length of the bolt holding two wooden members of the ship frame. The bolt and the wooden members are deformed due to shear stress

The most curious mechanical fasteners found were threaded rods and turnbuckles on wreck A (Figs. 6–7). No analogs have been found on other wrecks. It was first supposed that the rods were either alien to the structure of the vessel (installed years later to transport the wreck, supposing that it was an obstacle to navigation), or were somehow utilized to secure cargo. However, it seems more likely that these were initial structural elements of the vessel. The rods and turnbuckles supposedly held the mooring posts; they were pinned to the floor of the barge and stretched to the deck, thus, giving us information on the vessel's depth. A key feature of this component, allowing us to more or less accurately date the vessel is the design of the turnbuckles. An analysis conducted by the Department of Welding of Flying Apparatuses concluded that the turnbuckles were made by welding two iron plates to two hollow cylinders with an inside thread. The type of welding used was arc welding. Fig. 6 is a testament to this observation; traces of the weld pool are still visible on the structure. Consequently, vessel A could not have been built prior to the 1930's; even at that time there

would hardly be enough welding apparatuses in Siberia. It is known, for instance, that among the first recorded incidents of arc welding in the Soviet Union in shipbuilding took place in 1930. Archival evidence let us establish that by 1936 there was at least one electric arc welding apparatus at Igarka; its power consumption was 30,144 kWh [5, L. 36]. So, it is quite likely that wreck A was either built in the 1930's, or some of its components were installed at that time.



Figure 6. A turnbuckle with two threaded rods from wreck A. The weld is clearly seen.
The upper plate buckled



Figure 7. Another turnbuckle from wreck B

4. An inquiry of the types of failures

However effective these fasteners were, they still could not prevent various types of failure resulting in the heavy stress endured by the vessel from excessive loads, harsh sea conditions, etc.

The current condition of the wrecks shows that most of the fasteners are still intact despite being massively deformed. This is, primarily, a result of the wood decay. Some of the surviving wooden members also reveal various cases of failure due to stress. Among the discussed types of failure in this paper will be failure modes for bolted joints and

As we have found no signs of sheared bolts or nails, shear failure of the metal fasteners seems to have been a minor concern. However, it affected the wooden members to some degree; as the vessel rocked on the waves (usually, an up and down motion), shear stress caused deformation around the bolt holes (Fig. 5). Bearing failure of the wooden structures also seems to have been an insignificant concern, due to the properties of wood to withstand

such deformation; many of the washers are embedded into the wood – a result of overtightening and the expansion of moist wood.

Considering the threaded rods, their deformation can be clearly visible on the first wreck. As the rods are all deformed in one pattern, it can be suggested that this was a result of the deck collapsing and compressing the rods and turnbuckles, which acted as slender columns and buckled. Using Leonhard Euler's critical load equation

$$P_{cr} = \frac{\pi^2 EI}{L^2}$$

where I is the smallest moment of inertia for the cross-sectional area of the column, we can find the critical load that causes an ideal column (secured at both ends) to buckle [10]. In our case, the column is pinned at both ends, as the turnbuckles allow it to rotate around its axis, thus, K (the effective length factor) = 1.

Likewise, we can find the load that caused the deformation of the threaded rods, by rewriting Euler's equation

$$P_{cr} = \pi^2 EI / L^2 = \pi^2 E / L^2 \pi d^4 / 64 \rightarrow d = \sqrt[4]{(64 P L^2 / \pi^3 E)}.$$

Further modifications of Euler's critical load equation can incorporate the effective length factor ($K = 1, 0.5, 0.7, 2$)

$$P_{cr} = \pi^2 EI / (KL)^2;$$

the Euler stress can be calculated

$$\sigma_{cr} = \pi^2 E / (KL / r_G)^2 \quad [10].$$

The turnbuckles would be the element that tensile stress would be most exerted on. The welded joints would be the most vulnerable part of the component. However, as seen from the images, either the tension was little, or the joints proved strong enough.

While there is not necessarily anything new in the behavior of these components in terms of structural mechanics, it is possible, by using materials science, to extract some new historical evidence concerning the vessels' construction, its loss, and the environment in which the wreck has been found. Further inquiry into the issue shall be made to solve a number of topical issues.

5. Perspectives for metallurgical analysis

A study of metal fasteners from the RMS *Titanic* and comparing them with other iron components of the period has been discussed in [8]. The paper provides us with a scientific apparatus for performing experiments on the metal fasteners, collected from wreck A. It is planned that the perspective work shall include the following: microstructural examination and image analysis for slag contents (optical microscope), mechanical testing (materials testing machine), and micromechanical analysis. The collected specimens will be compared with other components of the period, e.g. railway spikes from the Trans-Siberian Railway.

It has been ambitiously proposed that a complex metallurgical analysis can even be used to date metal objects. The method can be basically outlined in the following thesis: let us

suppose that we have at our disposal two metal components that have been produced at the same time from the same material, and using the same technological process; in this case a high probability exists that these two components are able to endure similar loads and withstand similar stresses and strains; their microstructures will also be similar. The method is absolutely theoretical and has, to our knowledge, not been proposed in literature. At the same time this dating method, which is based on material properties and strength of materials, offers an alternative to more traditional approaches, such as radio-carbon dating and dendrochronology.

6. Conclusion

The conclusion to be derived is that Siberian shipbuilding during the first decades of the Soviet era was in sufficient deficit of industrial building materials. Mechanical fasteners had to be produced on site using whatever rudimentary methods available or delivered at high costs to the local wharves. Using various methods from structural mechanics and physics, it is possible to obtain new evidence on the structures of the first vessels that were employed in the Kara Sea Expeditions.

Further research is planned after sufficient financial support will be obtained. It is also planned to collect more specimens from shipwrecked vessels on the Yenisei to conduct a complex analysis of the structural members and mechanical fasteners of nineteenth and twentieth-century vessels. The results of these investigations may later be used to reconstruct one of the more prominent vessels – the schooner *Utreniaia zaria*.

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