NEW INSIGHTS ON CLASSIFICATION OF IRON-CARBON ALLOYS, SPECIALLY HIGH CARBON STEELS, IN RASARATNASAMUCCAYA

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The categories of iron-carbon alloys mentioned in Rasaratnasamuccaya have been critically discussed, with particular attention to the high carbon varieties (wootz steel). The most characteristic feature of high carbon steel (ティッガラ loha) is pogara, which has been shown, for the first time, to be the solidification cavity seen in the centre of the top of the wootz ingot. The connection of pogara with the term pulad used for wootz steel in several parts of the world has been pointed out. The knowledge on origin and roots of words from language studies can be usefully combined with knowledge on metallurgical/material issues from archaeometallurgical studies to open up new lines of thought.

Key words: High carbon steel, Kāntā loha, Khara loha, Munḍa loha, Tikṣṇa loha, Pogara, Rasaratnasamuccaya.

INTRODUCTION

The origin of the science of metals and minerals in India can be traced to early times, beginning from the pre-historic period (4500-1500 BC). Several metallurgical and chemical practices like casting, forging and smelting were known to the people of the Harappan Civilization. These practices progressed positively in next period (1500 BC-600 BC) when references to many metals and minerals can be noted in the four Vedas. The Atharvaveda in particular appears to have been the original source for later practices of Rasaśāstra (the science of mercury and minerals) mentioned in

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the Upaniṣads, Śrutis, Brāhmaṇa and other scriptures. The next period termed as Ayurvedic period (600 BC-800 AD) can be identified as the golden period. Significant works such as Caraka Saṃhitā and Suśruta Saṃhitā were produced in the first half of this period. The Arthaśāstra of Kautilya (321 BC-396 BC) provides a systematic and scientific account of smelting of many metal ores. The evolution of advanced Rasaśāstra took place in the period between 500 AD and 1600 AD when several texts came into existence with increasing activity in this science. The aims of Rasaśāstra appears to have been two fold - conversion of base metal into gold and silver (lohaiyā or rasavidyā) commonly called as alchemy and use of scientific knowledge for curing diseases to achieve perfect health (dehavidyā). One is truly wonderstruck by the vastness and depth of the knowledge acquired by scholars of this period where the physical and pharmacological properties of many metals and ores, and the processes of smelting the ores have been detailed. This truly attests to the evidence of consistency and depth of knowledge of advanced metallurgy.

The earliest available text of Rasaśāstra is Rasāhṛdayatantra of Govinda Vāgbhaṭapāda dated to early 800 AD. During the same period, several scriptures attributed to Nāgārjuna (possibly more than five persons with similar name), the father of Rasaśāstra are mentioned (like Nāgārjuna tantra, Rasaṅgatākara, Yogaratnamālā, Rasendra Maṅgala, Rudrayāmala tantra, Yogaśataka, Ārogvamanjari, etc.). The authorship of Rasaṅgatākara has also been attributed to Nityanātha Siddha.

The important works written between 800 AD and 1600 AD and available in published form are Rasopaniṣat by Somanātha (1000 AD), Cakradatta by Chakrapāni Datta (1100 AD), Basavarajīyam by Bāsavaraja (1100 AD), Ānandakāṇḍa by Bhairavanātha (1200 AD), Kākacandrīṣvara tantra by Kākacandrīṣvara (1200 AD), Rasendracuḍāmaṇi by Somadeva (1200 AD), Rasāṃrava by Bhairavananda Yogi (1200 AD), Rasaparakṣasudhākara by Yaśodhara (1400 AD), Rasaratnasamuccaya by Vāgbhaṭa (1400 AD), Rasendrasārasanigrha by Gopalakṛṣṇa Bhaṭṭa (1400 AD), Rasakaumudi by Ganacandra (1500 AD), Rasasanketakahākā by Cāmuṇḍa Kāyastha (1600 AD), Rasakāmadhenu by Śri Cuddāmani (1700 AD), Rasacandrāṇṣu by Dattaram Vaidya (1700 AD) and Ayurveda Prakāṣa by Madhava Upādhyāya (1700 AD).
Rasaratnasamuccaya is a work of Rasaśāstra written sometime between 1300 AD and 1400 AD. The author of the text agrees right in the beginning that the work is not original and it is a compilation of existing knowledge borrowed from the works of several scholars (also quoted in the text). This text is credited as being the first systematic work on Rasaśāstra as aptly summed up by Prafulla Chandra Ray in his History of Hindu Chemistry as "a systematic and comprehensive treatise on materia medica, pharmacy and medicine. Its methodological and scientific arrangement of the subject matter would do credit to any modern work and altogether it should be pronounced a production of unique of its kind in Sanskrit literature."2

The author of Rasaratnasamuccaya has been called as Rasa Vāgbhaṭa to distinguish him from other famous authors with similar name Vāgbhaṭa. The greatness of the author lies in the manner in which extremely scattered and disintegrated information available from earlier original sources were put into a comprehensive and handy compilation, thereby making Rasaratnasamuccaya as one of the best works of Rasaśāstra1. The first eleven chapters deal with properties and medicinal aspects of minerals and metals, while the chapters from twelve to thirty deal with prepared formulations for treatment. Chapter five is of particular interest from a metallurgical perspective because as the first verse announces the important metals (svarna or gold, rajata or silver, tāmra or copper, loha or iron, naga or lead and vaṅga or tin), alloys (pītala or brass, kāmsa or bronze and vartaloha or bell metal). Several aspects and properties of these materials are described in this chapter.

It is important to critically look at the verses 67 to 96 of chapter five of Rasaratnasamuccaya because iron-carbon alloys have been classified. The main aim of the present analysis is to understand the properties of high carbon steel (or wootz steel) based on this classification. The text of Rasaratnasamuccaya in chapter five from verses 67 through 96 will be reviewed in the form of an executive summary. The Dravidian Etymological Dictionary Revised (DEDR)3 and Comparative Dictionary of Indo-Aryan Languages (CDIAL)4 will be utilized for understanding the meaning of the terms used in Rasaratnasamuccaya. New interpretations, that have a bearing on the wootz problem, will be proposed.
Executive Summary

Atha loha:

\[ \text{muṇḍam tīkṣṇaṇca kāntaṇca trividāramayāṃ smṛtam} \]
\[ \text{mṛdu kunṭaṇ ca trividāram muṇḍamucyayē} \parallel 67 \parallel \]
\[ \text{kharaṃsāraṇca hṛṃnālaṃ tārā vaṭṭaṇca vājiram} \]
\[ \text{kālalohabhidhāmaṇca śaḍvidhaṃ tīkṣṇamucyate} \parallel 68 \parallel \]
\[ \text{bhṛmakaṇicumbakacāiva kārṣakaṇ vrāvakāṇ tathā} \]
\[ \text{evaṇcaturvidhaṇ kāntam romakāntaṇca paṇcamaṃ} \parallel 69 \parallel \]

Varieties of loha:

Loha\(^5\) is remembered (smṛtam) of 3 types: muṇḍa, tīkṣṇa, kānta. Varieties of muṇḍaloha are three: mṛdu, kunṭha, and kaḍāra. Varieties of tīkṣṇa are six: khara, sāra, hṛṃnala, tārāvaṭṭa, vājira, and kālaloha. Varieties of kānta are five: bhramaka, cumbaka, kārṣaka, dravaka, and romakānta.

Atha muṇḍam:

\[ \text{mṛdu kunṭaṇ ca trividāram muṇḍamucyayē} \]
\[ \text{dutadrāvamavisphoṭam cikkaṇam mṛdu tacchubham} \parallel 70 \parallel \]
\[ \text{hatam yatprasareddukkhat tatkunṭam madhyamāṃ spṛtam} \]
\[ \text{yaddhatam bhāyate bhānge kṛṣṇam sūttatakaḍārakam} \parallel 71 \parallel \]

Varieties of muṇḍaloha\(^6\):

Muṇḍaloha is of 3 types: mṛdu, kunṭa and kaḍāra. Mṛdu is auspicious; it is that which melts quickly on heating, does not break on beating, which is soft and cikkana (slimy). Kunṭa is one which spreads with difficulty on beating; this is of medium type in qualitative grade. Kaḍāra is inferior loha, breaks if beaten, broken surface is black in colour [mṛdūkāṣṇayasa ‘soft-iron’ (Skt.)].

Properties of muṇḍaloha:

\[ \text{muṇḍam param mṛdulakam kaphavātaśūlāmūlāmamehagada} \]
\[ \text{kāmalapānḍukhāri} \]
\[ \text{gulmāmavātaṣṭhāharārtiharaṇ pradvipī sōpapahaṇ rudhiraṇkṛtakhala} \]
\[ \text{kosthaśodhi} \parallel 72 \parallel \]

Muṇḍaloha is very soft; used in alleviating kapha and vataśūla, arśa, āmadoṣa, prameha, kāmala, pāṇḍu, gulma, āmaṭīā, udāraṇgā and sopha. It improves appetite, enhances blood and effects kṣīṭhasuddhi.
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aśuddhaloham na hitam niṣevaṇādāvurbalam kāntivināśi niścitam
| hṛdi prapiḍāṃtanute hyapāṭavaṃrujam karotyeva viśoddhya mārayet || 73||

Consuming bhasma prepared from aśuddha (impure) loha is unwholesome. It destroys the strength, complexion and reduces the life-span. It causes hṛdaya śula and śarira śaithilya leading to many diseases. So, the bhasma of the loha is prepared only after śodhana.

Atha tīkṣṇaṃ:

kharaṃ sāraṇca hṛṇnalaṃ tārāvataṅca vājiraṃ |
kālalohābhidhānāca śaṭvidhaṃ tīkṣṇamucyate || 74 ||
puruṣam pograronmuktam bhinge pāradacacchavi |
namane bhāṅguraṃ yattakharalohamudāṛtam || 75 ||
vagbhaṅguradhāraṃ yatsāraloham tāḍirītatam |
pogarābhaṅsakaṃ pāṃḍubhūmiṃjaṃ sāramucyate || 76 ||
krṣṇāṇaṇāvapunācchavi ījatulyorupogaram |
chedane catipuruṣam hṛṇnalamiti kathyate || 77 ||
āṅgam chāyā ca vaṅgaṇca pograsyābhidhārjayam |
cikuraṃ bhāṅguraṃ lohātpogaram tatparam saṃṭtam || 78 ||
pogarairvajrasaṅkāśaiḥ sūkṣmarekhaisca sāndrakaiḥ |
nicitam syāmalāṅgāṇa vājiraṃ tatprakīryate || 79 ||
nīlakṛṣṇaprabham sāndram mahāṃ guru bhāsuram |
lohaṅgātepyaṅgāṅgadhāraṃ kālāyasaṃ matam |
kharalohātparam sarvamekaikasmācchatottaram || 80 ||

Varieties of tīkṣṇaṃ:

Tīkṣṇaloha are of six types: khara, sāra, hṛṇnala, tārāvata vājira and kālaloh. Khara tīkṣṇaloha⁸ is spotty, “rough, uneven, hard” (puruṣam⁹), pogaromuktam (with released holes). Broken surface is lustrous like mercury. It breaks when bent.

Edge of sāra tīkṣṇaloha¹⁰ mutilates when hit hard. It has a semblance of pogara (released holes). Found in whitish yellow earth.

Hṛṇnala tīkṣṇaloha¹¹ is dull white in colour; has pogara (released holes) which resemble castor seeds. This loha is extremely hard and very difficult to break.
Anīga, chāya, vaṅga\textsuperscript{12} are (dhatra ‘receptacles’) — synonyms of pogara. When the iron is broken, brittle, hairy (cikura) lines and pogara (released holes) are seen.

Vajira tīkṣṇaloha is massive (solid) and very hard like vajra (diamond); it has minute lines and pogara (released holes) is black in colour.

Kalaloha is bluish black in colour, solid, slimy (smooth), heavy and lustrous; its edges are not mutilated even by the impact of beating.

Among all the six types, that is, khara, sāra, ḫṛṇnāla, tārāvatta. vajira, and kātaloha, each is one hundred times superior to the previous type (e.g., sāra is 100 times superior to khāra and so on).

Properties of kharaloha:
rūṣaṃ syāt kharalohakaṃ samadhuraṃ pāketha vírye himaṃ |
tiṣṭhaṃ kaphapittakṣṣhajāharaṇautī hámapāṇadvartinut |
sadyah śūlayakṛṣṭgadakṣayajaraṃmahāmavātāpahāṃ |
dīptiṃcāticārasāyaṇamaṃ balakaraṃ dunārmadāhāpahāṃ || 81 ||

Khara tīkṣṇaloha is rūṣa\textsuperscript{13} (astringent): had madhura pāka, śita vírya, tikta rasa and is hot to touch. It alleviates kapha, pitta, eradicates udara, piliharoga, āmadosa, pāṇḍu, śūla, yakṣī vikāra, kṣaya, daurbalya, prameha, āmahāta, arṣa and dāha. It is a very good rasāyana and is nutritious.

Atha kāntam:

bhṛamakaṃ cumbakāncaiva karsakaṃ drāvakaṃ tathā |
evam catuvridham kāntam romakāntaṃca paṇcamaṃ || 82 ||
ekadvidrīcatuspaṇcasaarvatomukheiva tat |
pitau kṛṣṇau tathāraktaṃ trimvarnaṃ syātprthak prthak || 83 ||
krameṇa devatāstrata brahmaviṣṇumahēsvarāḥ |
sparsvavedhi bhavetpitaṃ kṛṣṇau śreṣṭham rasāyane || 84 ||
raktavarṇam tathācāpi rasahandhe praśasyate |
bhṛmakaṃ tu kaniṣṭham syācumbakaṃ madhyamaṃ tathā |
uttamaṃ karsakaṇcaiva drāvakaṇcottomottamam || 85 ||

Varieties of kāntaloha\textsuperscript{14}:

Kāntaloha is of five types: bhṛmaka, cumbaka, karsaka, drāvaka, and romakānta. The varieties of kāntaloha are: ekamukha, dvimukha,
trimukha, caturnukha, pañcamukha and sarvatomukha. By colour, it is of three types: pīta (yellow), kṛṣṇa (black) and rakta (red). In each divinities Brahmā, Viṣṇu and Mahēśvara are respectively situated. Piṭakānta is sparśavedhi (that which turns anything into gold by mere touch), kṛṣṇakānta is the best rasāyana; rakta kānta loha is used to make inert (baddha). Bhṛma is inferior, cumbaka is medium and kārṣaka is superior; drāvaka kāntaloha is the best of all.

Properties of kāntaloha:

bhṛmayaellohajātaṁ yattatkāntaṁ bhṛmakaṁmatam
cessayiccumkaṁ kāntaṁ kārṣayetakākathā||86||
sākṣad yaddrāvayellohaṁ tatkāntaṁ drāvakah matam
 tadromakāntaṁ sphaṭijādyato romodgamo bhavet||87||
catuspañcamukhaṁ śreṣṭhamuñcamaṁ sarthomukham
 bhṛmakaṁ cumbakaṁ caiva vyādhanese praśasyat̄||88||
 rase rasāyane caiva kārṣakaṁ drāvakaṁ hitam
 madonmattagajāṁ sītaḥ kāntamakusumucyaṁ||89||
 kṣetrajñānāvārdhātvaṁ tatprayatnena dhīmatā ā
 marutā tapaviṁśiptaṁ vajrayennatra san śayaṁ||90||

When small pieces of iron are brought near the kāntaloha and if these pieces tremble a bit and revolve around. Such a kāntaloha is bhramaka kāntaloha.

Iron pieces are attracted and get attached when brought near the cumbaka kāntaloha.

Kārṣaka kāntaloha attracts the iron pieces towards it.

Drāvaka kāntaloha attracts iron pieces even from a far off distance (or it can repel the pieces).

Iron pieces brought near romakāntaloha stand erect like hairs. Kāntaloha which has four or five faces (planes) is the best. The variety which has the faces (planes) on all directions is extremely good. Bhramaka and Cumbaka can eradicate diseases. Kārṣaka and drāvaka are used in rasa karma and rasāyana karma.

Kāntaloha is like aṅkuśa (goad) for the parade which is like an inebriated elephant.
A smart physician collects kāntaloha by selecting a proper kṣetra (region). Kāntaloha undoubtedly gets vitiated by polluted air and it discards sunrays.

**Features of superior kāntaloha:**

pātre yasya prasarati jale tailabindurna liptam  
gandhaṃ hingu tyajati ca tathatiktaṇāṃ nimbakkalkaḥ  
pāke dugdhaṃ bhavati śikharākāraṇā naiti bhīmau  
kāntaṃ lauham tadidamuditam lakṣaṇoktaṇ canānyat 91

In a vessel made of kāntaloha containing water, if a drop of oil is put, the oil does not spread. The smell of hingu (asafetida) vanishes when smeared inside the vessel of kāntaloha. The bolus (kalka) of nimba loses its bitterness after sometime. Milk when heated in a kāntaloha vessel boils up to the brim of the vessel but does not spill over the rim of the vessel.

Kāntaloha possessing these features is said to be the best and other types are discardable.

**Properties of kāntaloha:**

kāntayo tirāśayanottarataraṇ svasthe cirāyuhpradaṇ  
snigdhaṃ mehaharaṇa tridoṣāśāmanāṃ śālamamulāpaham  
gulmapliḥ hayakṛtkṣayāmayaharaṇaṃ pāṇḍūdaravayādhinu-  
tiktoṣṇaṃ himavi ryakaṃ kimaparaṇaṃ yogena sarvātīrṇut 92

Kāntaloha is the best rasāyana; enhances life-span when consumed by a healthy person. It is snigdha, alleviates all doṣa. Kāntaloha eradicates diseases like prameha, āmadoṣa, arṣa, gulma, yakrit, plīhā, pāṇḍū, udara. It is tikta in taste, hot (to touch) and has śīta virya (or, both śīta and uṣna). If bhaṣṇa of Kāntaloha is taken along with proper anupāna, it can cure all kinds of diseases.

**Loha: śodhana-māraṇa:**

samyagauṣadhakalpāṇaṃ lohakalpaḥ praśasya 93  
tasmāt sarvapravattnena sūddham lohañca mārayat  
nāyāḥ pacentpaṇcapalādāravagūrdhvaṃ trayodaśāt 94  
ādau mantraśatāḥ karma kartavyaṃ mantra ucyate 95  
oṃ amṛtiodbhāya svāhāḥ anena lohamāraṇam 96  
lakṣottarāṇaṇaṃ sarvaṃ lohaṃ syāduttarottaram  
kāntaṃ koṭigunaṇaṃ tatra tadapyevaṃ guṇottaram
Of all medicinal preparations, *loha kalpa* are excellent.

Superior variety of *loha* is obtained, subjected to *śodhana* with effort and then subjected to *māraṇa*. If *loha* is taken for the process of *māraṇa*, it should not be less than five *pala* (that is, 12 *tola* or 200 *gms*) or more than sixteen *pala* (64 *tola* or 704 *gms*.)

A mantra, *Oṃ amritodbhavāya svāhā*, is chanted before commencing the process like *māraṇa*.

*Tīkṣṇa loha* is superior to *munḍaloha*, and *kāntaloha* is superior to *tīkṣṇa loha*. *Kāntaloha* is a crore times superior to all other types of *loha*.

**Characteristics of High Carbon Steels**

The above executive summary of the relevant verses related to iron that appears in the *Rasaratnasamuccaya* has been provided so that the reader has the first hand information on the actual verses in the text as well as the most modern translation. We come to know that iron carbon alloys were classified into three broad categories — *munḍa loha*, *tīkṣṇa loha* and *kāntaloha*. It is clear from the nature of these three different categories that *munḍa loha* represented very high carbon containing ironcarbon alloys (one that we may in modern parlance call cast irons), *tīkṣṇa loha* was the name given to high carbon steels, and *kāntaloha* low and medium carbon steels. In order to aid visualization, the approximate composition ranges for these three categories of iron-carbon alloys are shown in the Iron-carbon phase diagram of Fig. 1.

As regards wootz steel, the important verses to focus attention are verses 74 through 80 where the six different varieties of high carbon steels (i.e. *tīkṣṇa loha*) are detailed. The root, *dhātu*, for *tīkṣṇa* is *ṭīj* in Sanskrit. The word *taījasa-vartini* means ‘crucible’. Thus, *tīkṣṇa loha* is directly related to crucible steel. We further realize that the word *tīkṣṇa* implies that this category of iron-carbon alloys was specially meant for cutting applications because of the association of sharpness with this name.

The precise translation of the verses will not be repeated here but we shall critically look at the verses from a metallurgical perspective. Six varieties of high carbon steel that was made by the molten process (i.e. wootz steel) have been mentioned. All the varieties appear to refer to as manufactured
wootz ingot and not the processed material. This is important because one class of people were involved in producing (or smelting) wootz steel ingots, which were wrought to the necessary shape by another set of skilled blacksmiths. Either the blacksmiths completely finished the product from start to finish, or the wootz was supplied in a semi-finished condition. These semi-finished ingots could be later wrought by another blacksmith to make blades/cutting objects of desired shape. Therefore there were different groups of blacksmiths involved in working wootz to the finished product.
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It is interesting here to note the skill of the Indian blacksmith in working with wootz steel. Reaumur\textsuperscript{16}, writing in 1722, was highly critical of Parisian artisans, because none of whom succeeded in forging a tool out of a cake of Indian steel. It is interesting to note that wootz steel cakes were worked and then sent to Europe. Moxon\textsuperscript{17}, writing in 1677, specifically mentions that wootz steel “very rarely came unwrought into England.”

In the following discussion, we shall critically review three properties of wootz steel (i.e. high carbon steels) as mentioned in the Rasaratnasamuccaya. The most important characteristic of high carbon steels will be taken up in greater detail after discussing the first two properties.

Two common properties mentioned for the medium carbon steels in the Rasaratnasamuccaya verses 74-80 are, first, they were lustrous (verse 75 mentions that “broken surface is lustrous like mercury” while verse 80 specifically mentions “lustrous”), and secondly, they possessed lines on the surface (verse 78 where mention is made that “when the iron is broken, brittle, hairy lines are seen” and verse 79 also mentions “\textit{vājira tī kṛṣṇa loha} has minute lines”). The lustrous nature of the broken surface is clearly due to the presence of cementite in the wootz steel ingot. We notice the same kind of bright fracture in iron carbon alloys containing higher amounts of cementite\textsuperscript{18}. The fine lines that are mentioned refer to the large cementite bulky precipitates of cementite that are arranged in a particular pattern which appears as lines to the observer of the wootz ingot and this is due to the manner in which the ingot solidified in the crucible (generally slow cooling rate). In fact, the importance of these aligned cementite streaks (i.e. these lines on the surface) in obtaining fine quality cutting object is evident when one compares verse 78 where the best quality wootz steel (namely \textit{vājira tī kṛṣṇa loha}) is said to possess “minute lines” which implies that an aligned arrangement of finer carbide particles in the original wootz steel ingot resulted in good cutting properties in the finished product.

Recent research has revealed the presence of different types of cementite particles (large bulky carbides elongated carbides along grain boundaries, carbide from pearlite at some locations in grain boundaries and spheroid carbides in the matrix) are present in wootz steel objects\textsuperscript{19}. New insights that have been obtained on the nature of these different types of cementite particles by electron back scattered diffraction technique have been
explained by Barnett and Balasubramaniam\(^9\) in the thematic issue following this one. The most important observation to note is that carbon is mainly present in wootz steel ingots and objects made of wootz steel in the form of cementite and not as carbon or graphite.

**Critical Analysis of Pogara**

Now let us focus on one common (and important) characteristic of the high carbon steels mentioned in these verses. Verses 75 to 79 clearly state that one of the characteristic features of tīkṣṇa loha is that it contained pogara. This is a very important term because this specifically is mentioned in Rasaratnasamuccaya while describing five types out of the total six types of tīkṣṇa loha. This has been generally translated as “hair like lines” and thereby related to white cementite streaks, that were coarse enough to be seen by the naked eyes\(^21\).

However, this may not be the appropriate translation. In order to arrive at some conclusions, let us look at a set of glosses for understanding the term pogara used in describing tīkṣṇa loha. These are: pogulu a hole (Ka.); pokor hollow; bogga small hole, perforation (Kol.); hole (Nk.); bonga hole (Ga.) (Dravidian Etymological Dictionary\(^3\) DEDR 4452). Further, we notice that association of carbon/charcoal from the terms bog (pl. boggul), bogum (pl. bogmul) ‘charcoal, carbon’ (Parji) (DEDR 4460).

It is also important to note the context in which the term pogara appears in the text. For example in verse 75, the specific term used is paruṣam pogaronmuktam. The term pogara clearly means “hollow, hole” as described above. We next pay attention to the term paruṣam and this has been translated in the executive summary as from the origin barusu rough, coarse; parusapu hard, harsh (Telugu) (DEDR 3973); paruṣa hard (Skt.Pali) (CDIAL 7910). This is also closely tied with another way to look at the term as “paruṣam pogaronmuktam” whereby “paruṣa” means “pupil of the eye” (Śatapatha Brāhmaṇa) and “muktam” implies “that which is released” (as a weapon released from, say, dhanus). Thus, read with “paruṣam,” the phrase “paruṣam pogaronmuktam” may be reference to a small hole (like pupil of the eye) released on the metal.

We next have to look at the metallurgical implications of this interpretation, namely release of tiny circular holes (like the pupil of the eye)
on *tīkṣṇa loha*. There is no satisfactory explanation for the term *pogara* because the metallurgical implications have not been discussed earlier in the literature, but for the translation of *pogara* as "hair-like lines". The reason for lack of detailed discussion is because there was no physical evidence on which the connection can be made, due essentially to lack of actual wootz steel ingots. However, during the course of a thorough study of wootz steel currently underway at IIT Kanpur, two original wootz steel ingots were obtained from Telangana region. They were of two different sizes. However, both appear similar in shape, in that they are concave at the bottom and almost flat on the top side (see Fig. 2 for side view of the ingots). The larger one is approximately 11 cm in diameter and 2.5 cm in thickness in the thickest portion, while the smaller ingot is approximately 6.5 cm in diameter and 2 cm in thickness at the thickest portion. The larger wootz ingot was obtained from Konapuram village in Nizamabad district of Andhra Pradesh and its weight is 1.5905 kg. The smaller wootz ingot was obtained from a senior blacksmith called Mandalogi Gangaram from Konapuram in Khammampalli Mandal of Nizamabad district of Andhra Pradesh and it weighs 0.4254 kg.

The bottom view of the wootz ingots are shown in Fig. 3. The bottom of the wootz ingots was in contact with the crucible and generally takes the shape of the bottom of the crucible. In both these cases, the bottom appears with a small concavity indicating the nature of the bottom of the crucible in which it was made. The top surfaces of the wootz ingots are shown in Fig 4. Particular attention must be focused on these images because the interesting observation that is evident is that when one looks at the ingot from the top, there are circular marks in the center, very much like the possible description in the *Rasaratnasamuccaya* verse 75, namely like "pupil of the eye". In metallurgical terms, it is very easy to understand this as solidification cavity.
Fig. 3. Bottom view of the two wootz ingots

Fig. 4. Top surface of the two wootz ingots. The solidification cavity at the centre of each ingot has been arrowed

resulting from the solidification of the wootz ingot in the crucible. In fact, the description given in the *Rasaratnasamuccaya* aptly is a remarkable description of solidification cavity. Therefore, the characteristic feature of all wootz ingot was that they were solidified after melting steel and further the ingots appear to have been cooled down slowly after the process of wootz steel making in crucible was over. This would result in the solidification cavity like that noticed on the top surface of wootz steel ingots, i.e. the surface not in contact with the crucible.
Fig. 5. Castor seeds showing that their characteristic shape is oval and not circular.

It is also easy to appreciate why there were no good interpretations of the term pogara in the past. The problem was that the earlier scholars just did not know how an original wootz ingot looked like and therefore the correlation of the term to the characteristic feature on the wootz ingot was missed. Due to the availability of these two original wootz ingots, it has been possible to interpret the term pogara with the solidification cavity seen in the centre of wootz ingot and therefore the particular way in which the material solidified in the crucible was also important while classifying the different types of tīksṇa loha.

Further in verse 77, we notice that the hṛmnāla variety of tīksṇaloha is mentioned as possessing pogara which resemble castor seeds. Fig. 4 shows castor seeds, from which it is easy to conclude that the solidification cavity in case of this category of high carbon steel was not perfectly circular in nature but slightly oval in nature.

Finally we may end the discussion on pogara by noting its close phonetic relationship with the term pulad (and its variants), which was widely used in several different parts of the world. The present discussion provides some valuable clues that the term pulad could originate from the characteristic feature noticed in all the wootz ingot, namely the solidification cavity, which was called in the local dialects and even so prominently in the Sanskrit text Rasaratnasamuccaya (not one time, but five different times while referring to steel used for cutting applications, namely tīksṇa loha) as pogara.
CONCLUSIONS

The classification of different categories of iron carbon alloys in the Rasaratnasamuccaya has been critically discussed. Special attention was focused on high carbon steels that were called by the general term of tıkṣṇa loha and its further subdivision into six varieties. The most characteristic feature of tıkṣṇa loha is pogara and this has been analyzed to show, for the first time, that this implied the solidification cavity seen in the centre of the top of the wootz ingot. It has been proposed that the origin for the term pulad (and its many variants) is this term pogara. The present study further shows how knowledge on origin and roots of words from language studies can be fruitfully combined with knowledge on metallurgical/material issues from archaeometallurgical studies to open up new lines of thinking.

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REFERENCES

5. aýas ‘iron, metal’ (Rgveda.Skt.), aýírda karba ‘iron’ (Tulu); atar fine sand (Ta.); aduru id. (Ka.) (Ta. lex.), aduru native metal (Ka.); adaru a sparkle; dear, costly (Te.); aýil iron; beauty; avir splendour (Ta.); avir iron dust, any ore (Ma.) (Ka. lex.) cf. aril small sharp pebble (Ta.) (DEDR 209).
6. The category munḍam refers to cast iron of high carbon content which Indians generally did not prefer. Therefore, another interpretation could be iron dross. That this was not valued is also evident from the value of different categories of iron mentioned again
in Rasaratnasamuccaya. Tīkṣpam is cast (in the sense of molten) iron, sharp-edged iron, steel. Kāntaloha is iron that is certainly magnetic, for example magnetite (also, lodestone), which is referred in Sanskrit as kāntāyasa. Note also, munaṭṭam ‘iron dross’ (Tamil) munḍaja ‘steel’ (Skt.)

7. tīkṣya ‘iron’ (Skt.): harsh. rough, rude Mn. vii. 140 Mahābhārata; sharp. keen Pāṇini. 5-2; root: tīj ‘to be or become sharp’ Rigveda i. 55.1: iii.2,10 and 8,11; tejate ‘is sharp, sharpen (RV); tīkṣya sharp (RV); tikkhālāja sharpened (Pkt); tikha ‘steel’ (Assamese); tikhe-‘steel’ (Marathi); tikhā thin, sharp, edged metal or glass bracelet (Oriya); tikho ‘sharp, pointed’ (Nepalese) (CDIAL 5839); tikhāro spark (G); tikkhārē to sharpen (M). (CDIAL 5840). teqe to shine, glow; tēg-tegē to be or become glossy (Maltese) (DEDR 3201); āṅīq-(-t) to sharpen (Pe.); tīti kīli id. (Kuvi)(DEDR 3273); tiṅḍrinu, tiṅḍrincu to shine (Telugu) (DEDR 3266)

8. khara- rough; saw (Pali); karakaya- saw (Pkt)(CDIAL 2819) garaku, garku, garasu a jag, notch, dent, toothed part of a file or saw, rough part of a millstone, irregular surface, sharpness (Kannada): kara sharp: karagasamu a saw (Telugu)(DEDR 1265) karavāla ‘sword’ (Skt.) khara-‘hard. sharp. pungent’ MBh.. ‘solid’ Pan. khara ‘sharp, notched’ (Old Awadhi)(CDIAL 3819) kharasua ‘having a swift current, name of a river in Orissa’ (Oriya). (CDIAL 3825)]

9. barusu ‘rough, coarse’; parusapu hard, harsh (Telugu)(DEDR 3973); paruṣa ‘hard’ (Skt.Pali)(CDIAL 7910)

10. sāraloha ‘essence of iron; steel’ (Skt.)

11. hṛt ‘carrying’; nāla ‘tubular vessel’ (Skt.)

12. aṅgala ‘to gape, open’ (Kuvi)(DEDR 34). Caya ‘wounded’ (Pkt.); khayā ‘worn out. injured’ (Bengali)(CDIAL 3645) vaṅg- ‘to give birth’ (Gadba)(DEDR 5549); vaṅga (pl.) edge, cutting edge, end (Kuvi)(DEDR 5552).

13. rūkhma to smelt (Kuvi); rāga (ru-), ūrka (urk-) to be dissolved (Kuvi)(DEDR 661). cf. uruku (uruki) to dissolve, melt, liquefy, be fused (Ta.)(DEDR 661), rokaḥ brightness; rociś light, splendour, brightness. Flame (Skt.); rociṣṇu bright, resplendent, shining, brilliant; ruc, rucā light, lustre, brightness (Skt. ex.)

14. kāntaṃ ‘a class of crystals’ e.g. candrakārītaṃ (Skt.): also ‘magnet’(Skt.)


