Development of hardening technology for working surfaces of microsurgical instruments made of titanium alloy

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Abstract: The structure and properties of materials and working surfaces of needle holders were studied to improve the technology of their manufacture according to the characteristics of hardness and functionality of a microsurgical instrument. The types and modes of volumetric and surface hardening of VT6 titanium alloy (Ti-6Al-4V) using laser technologies adapted to the working surfaces of the tool are proposed. The possibility of using the alloy to replace maraging steel in the manufacture of needle holders is evaluated.

Using instruments made of heavy metals makes it more difficult to perform microsurgeries and increases doctor fatigue. In addition, working surfaces of needle holders often suffer from wear or local damage due to their insufficient wear resistance caused by unstable parameters of manufacturing processes. That’s why, using light and degradation resistant titanium and new technologies for instrument production will improve quality and efficiency of microsurgeries.

We suggest using a new material to manufacture needle holders and treat their working surfaces. It is VT6 titanium alloy (Ti-6Al-4V) with stabilized structure after heat treatment [1, 2]. In order to address the issue of hardness and wear resistance of working surfaces (a significant flaw of titanium alloys), laser machining is used. It increases the degree of treatment localization, accuracy, wear resistance [3-7], and robotic systems ensure stable machining conditions, which is important for microsurgical instruments. The foreign materials of working surfaces for needle holders have been replaced by the Russian materials and technologies that have no equivalents in foreign countries [12-18].

We studied the structure, microhardness of the samples of steel 03Kh11N10M2T2 and VT6 titanium alloy (KMIZ and Kazan National Research Technical University (KNITU-KAI)), metal of needle holder working surfaces and coatings made in Tatarstan and Germany.

The hardness of as-received (KMIZ) steel 03Kh11N10M2T2 is HRC 30, of VT6 titanium alloy is HRC 28. The average metal hardness (longitudinal) of atraumatic microneedle metal is HRC 45 (with a diameter of 0.4 mm), HRC 56 (with a diameter of 0.15 mm) [4]. A hardness of HRC 50 is achieved with heat treatment of steel 03Kh11N10M2T2 under conditions of quenching and age hardening, which have been proposed by KNITU-KAI (it satisfies the requirements for working instrument surfaces) [4]. Hardness of VT6 alloy subjected to harsh quenching and age hardening under different conditions is HRC 36 (Fig. 1). VK10 coating of instrument (Tatarstan) on steel 03Kh11N10M2T2 has a poor adhesion, it is not even and complete in the thickness range of 0 to 0.013 mm [4] (Fig. 2, a).
Figure 1. The microstructure of VT6 alloy (α + α\(^1\) + α\(^{11}\) + β): (a) “harsh” quenching (from β-region) and age hardening without high temperature thermomechanical treatment; (b) mild quenching (from α+β-region) and age hardening with high temperature thermomechanical treatment; (c) “harsh” quenching (from α + β-region) and age hardening; (d) “harsh” quenching (from α + β-region) and double age hardening. (×500 /×1300)

VK10 coating on the surface of VK6 (Tatarstan) instrument is very uneven, some areas are not covered completely, and its thickness range varies from 0 to 0.036 (Fig. 2, d). Deposited “diamond coatings” of needle holders (Tatarstan) are brittle, and their hardness is low (HRC 42) (Fig. 2, b). The working surfaces of needle holders (Germany) made of steel with the actual composition 20Kh15 ensure a hardness of HRC 51 for a discontinuous coating within the thickness range from 0 to 0.011 mm (Fig. 2, c). Plates made of W6C alloy welded to the needle holder (Germany) made of steel 20Kh13 (the Russian equivalent) have a hardness of from 73 to 75 HRC. As the used coatings of working surfaces in needle holders do not meet the requirements: they are discontinuous and peel off, welded plates are not easy to manufacture and impractical. Hence, the conventional methods of increasing wear resistance of working surfaces in needle holders are not very effective and not reliable.
Figure 2. Microstructure of working needle holder surfaces with the following coatings: VK10 on steel 03Kh11N10M2T2 (Tatarstan) (a), “diamond” (Tatarstan) (HRC42) on steel 03Kh11N10M2T2 (b), coating (Germany) (HRC51) on steel equivalent to 20Kh15 (c), plates VK10 on VT6 alloy (d), welded plates W6C (Germany) on steel 20Kh13 (the Russian equivalent) (e)

Laser technologies are the effective way to harden the martensite type of titanium alloys [3-6]. For the purposes of this paper, FMark-20 RL laser station and laser module based on LS-10 fiber oscillator were used as hardening sources [3]. Figure 3 shows the example of the sample for adjustment of laser hardening process, and the microstructure of one area (fusion) in VT6 alloy with as-cast structure. The microstructure was recorded with Auriga CrossBeam scanning electron microscope [8, 9] using SmartSem software.

Figure 3. Examples with the traces of laser machining: sample of VT6 alloy, structures of the area with partially melted metal and measured HV100 hardness.
Figure 4 shows the results of microhardness (HV, MPa) measurement in laser-machined areas (across and inward) of VT6 alloy and degree of laser hardening in relation to the base areas up to 167%, which corresponds to ~ HRC 60 under the following conditions of a laser generator: machining speed of V = 20 mm/s, number of runs of n = 20, average power of N = 20 (100 %), f = 21 500 Hz, laser spot size of d = 40 μm.

The structure analysis of laser-machined areas shows that the structure consists of heat affected zones, fusion zones, and a crater. It has the areas where it interacts with the environment directly, i.e. a crater (“plateau”) with melted heterogeneous structure of metal and area of melted structure, which is isolated from interactions, including the partially melted fragment. The hardness increases slightly above the base VT6 alloy in this area. The geometry of heat affected zones and specifically of fusion zones in titanium alloys depends significantly on the conditions of laser machining. In certain instances, laser machining can have negative results (alloy cracking) due to a combination of large thermal input of highly concentrated energy and some thermophysical properties of titanium [3]. It means that, with significant temperature gradients, the pressure of evaporating titanium vapors presses a portion of molten metal out. It increases the melting ability of a laser beam due to its deeper penetration through a small crater at the center of the fusion zone, which is sealed by melting at the last stage of pulse, then solidifies as a “plateau”. It was found with INCA X-MAX spectrometer that Ti and V were strongly oxidized and burnt out on the surface of the crater (Fig. 5). Such complex compounds as aluminum spinel, carbonitrides, and SiC are formed. With that, tremendous internal stresses occur and increase the brittleness of hard “plateau”.

![Graph](image)

\[
HV = 6E-06h^4 - 0,0073h^3 + 3,4197h^2 - 707,89h + 57650
\]

\[R^2 = 0,9738\]
Figure 4. Change in HV$^{100}$ hardness along the “plateau” in the y-direction (a) and inwards - h (b) from the crater to the fusion zone
Figure 5. Change in element-by-element composition of VT6 alloy inwards the laser-machined areas (from the crater to the fusion zone)

Phase age hardening should be used to provide stable properties, improve hardening of VT6 alloy after laser quenching with a hardness of > HRC 60. In addition to treatment localization and higher hardness, the positive effects are as follows: stable geometry and dimensions of microsurgical instrument. Hardening performance is defined by the increase rate of temperature gradient, nature of alloy interaction with the environment, and concentration of supersaturated phases $\alpha + \alpha_0 + \alpha^I + \alpha^{II}$ and $\beta_0$ of the transformed solution.

Meanwhile, performance and service life of working instrument surfaces are related to an increase in structural strength [1, 2, 10, 11], which is defined by the morphology of the phases [2] of the constituents of structure of phases $\alpha + \alpha_0 + \alpha^I + \alpha^{II}$ and $\beta_0$ of solid titanium alloy solution. It was analyzed how the key indicators of structural strength ($S_k$, $m^{(0)}$, $\psi$, and $E_k$) were influenced by a dimension ratio of $\alpha/\alpha_0$-phases (see Fig. 1) in the variants of alloy structural conditions. Figures 6-8 and [2] show the examples of conformance of the mentioned characteristics of the structure and the properties ($\psi$, $E_k$, $m^{(0)}\cdot 10^5$).
According to the defined regression coefficients: $R^2_1 = 0.9991$, $R^2_2 = 0.9969$ и $R^2_3 = 0.8542$ (see the curves in Fig. 6 и Fig. 7) the formulas:

$$\psi = 0.8928(\alpha/\alpha_n)^2 - 13.905(\alpha/\alpha_n) + 65.177$$

$$R^2 = 0.9991$$

$$E_K = 1170(\alpha/\alpha_n) + 656.1$$

$-\ E_K = f(\alpha/\alpha_n)$

- establish more stable connections than the formula (3) with a lower value of $R^2_3$ (according to the curve in Figure 8)

$$m^{(o)} \times 10^2 = -0.713(\alpha/\alpha_n) + 10.43$$

(3)
By solving (2) and (3) together with the formulas [7], we get a simple linear expression of true strength from the structure parameters [2]

$$S_k = 1700 - 41(\alpha/\alpha_p)$$  \hspace{1cm} (4)

![Figure 8. Relationship between phase ratio and strain-hardening coefficient](image)

Figure 8. Relationship between phase ratio and strain-hardening coefficient $m(\alpha/\alpha_p)$

The capabilities of the station based on fiber oscillator LS-10 with the protective cabin make it possible to use it as a pulsed laser deposition module. At the same time, the heat affected zone is minimal, which makes it possible to maintain the geometry and accuracy parameters of a fine instrument. Filler material is fed locally, the melting surface area reaches 90%. Figure 9 shows the structure and quality of adhesion of deposited film with the plate made of VT6 alloy, measurement of microhardness of melted deposit at the substrate. The element-by-element composition of deposited metal on the VT6 (Ti-6Al-4V) plate is given in the table.

| h, μm | C    | Al  | Si  | Ti   | V    | Cr    | Fe    | Ni     |
|-------|------|-----|-----|------|------|-------|-------|--------|
| 400   | 13.14| 1.28| 2.65| 9.27 | 0.18 | 7.17  | 3.07  | 63.25  |
| 525   | 7.29 | 4.18| 0.91| 54.33| 2.41 | 2.72  | 1.40  | 26.74  |
| 600   | 5.056| 5.84| 0.08| 85.30| 3.96 | -     | 0.11  | 0.13   |

![Element composition (%) in the areas of laser deposition at a depth of h](image)
The deposited metal in the melted area has an austenitic-carbide microstructure. No melted metal of the substrate made of VT6 base alloy was found. Pulsed laser deposition on VT6 (Ti-6Al-4V) plate increases a metal hardness within the range from HRC 70 to 80 at a depth of 560 μm, which exceeds the characteristics of working surfaces of the Russian and foreign needle holders. For instance, a hardness of HRC 73…75 is provided in the plates made of hard alloy (Germany).

Conclusions

1. The common deposited films on the working surfaces of needle holders with tungsten carbides on martensitic steels and VT6 alloy have a non-homogenous composition, thickness, and they are discontinuous.
2. Deposited “diamond coatings” of KMIZ needle holders are quite brittle, peel off, and their hardness is very low.
3. Plates welded to an instrument are not easy to manufacture, and they are impractical.
4. Therefore, the conventional methods of forming the working surfaces in needle holders are not always reliable, long lasting, and functional. A steel instrument has a higher weight and wears out users.
5. An instrument made of titanium alloy has a lower weight and higher corrosion resistance.
6. In terms of hardness and weight factor, proposed VT6 titanium alloy (Ti-6Al-4V) and variants of laser technologies (shock hardening and deposition) usually exceed the characteristics of working
surfaces of the needle holders made in Tatarstan, Russia and foreign countries, they can make microsurgery conditions more comfortable.

References
1. Murataev F.I., Zharzhanazi M.A. Provision of structural strength of titanium alloys according to criteria of ultimate plasticity and fatigue resistance // Vestnik of KSTU, 2013. No. 1. pp. 50-54. (in Russian).
2. Murataev F.I., Mukhamadeev I.M. Patterns of structural conditions and structural strength characteristics of pressed parts made of titanium alloy // Vestnik of KSTU, 2020. No. 2. pp. 50-58. (in Russian).
3. Murataev F.I., Klabukov M.A. Features of laser shock hardening for steels and titanium alloys // Vestnik of KSTU, 2012. No. 4. pp. 82-84. (in Russian).
4. Klabukov M.A., Danilov E.V. Rationale for composition of materials and technologies for working surfaces of microsurgical instrument // Vestnik of KSTU, 2019. No. 2. pp. 66-73. (in Russian).
5. F I Murataev et al Ranking materials technologies by limiting characteristics of heat-resistant alloys and their longevity in the problems of import substitution 2019 IOP Conf. Ser.: Mater. Sci. Eng. 570 012070.
6. Cao X et al (2009) Effect of welding speed on butt join quality of Ti-6Al-4V alloy welded using a high-power Nd: YAG laser. Optics and Lasers in Engineering. 47, pp. 1231-1241.
7. Murataev F.I., Khakimov S.Sh. Substantiation of microstructure and properties relationships of titanium alloys for prediction problems of fatigue resistance // Vestnik of KSTU, 2014. No. 3. pp. 110-113. (in Russian).
8. F I Murataev et al Substantiation of domestic material and welding technology for improving properties and competitiveness of pyrolysis furnace coils 2019 IOP Conf. Ser.: Materials Science and Engineering 570 012071.
9. Murataev F.I., Murataev A.F. Influence of composition and morphology of intermetallic phase of IN-738LC alloy on damageability of gas turbine blades // Vestnik of KSTU, 2015. No. 3. pp. 43-48. (in Russian).
10. Bratukhin A.G., Pogosyan M.A., Tarasenko L.V. Engineering and functional materials for today’s aircraft industry. M.: MAI Publ., 2007. 301 p.
11. Shkanov, I.N., Braude, N.Z., Murataev, F.I. Model of optimization of basic mechanical properties with respect to static and fatigue strength criteria in complex stress state conditions. // Soviet Aeronautics (English translation of Izvestiya VUZ, Aviatsionnaya Tekhnika) Volume 25, Issue 1, 1982, pp. 79-84.
12. Gabdrakhmanov A.T., Shafigullin L.N., Galimov E.R., Ibragimov A.R. Surface thermohardening by the fast-moving electric arch. IOP Conf. Series: Journal of Physics: Conf. Series. Volume 789 (2019), Article number 012010.
13. Gabdrakhmanov A.T., Israphilov I.H., Galiakbarov A.T. The study the erosion of the electrodes under the influence moving electric arc // Journal of Physics: Conference Series, Volume 567, Issue 1, 2014, Article number 012013.
14. Gabdrakhmanov A.T., Galiakbarov A.T., Samigullin A.D., Galiakbarov R.T. The calculation of a thermal field in the surface of a processed partunder the influence of a low-temperature plasma // IOP Conf. Ser.: Mater. Sci. Eng., Volume 134, Issue 1, 2016, Article number 012040.
15. Gabdrakhmanov A.T., Israphilov I.H., Shafigullin L.N. The metal surface cleaning using a vapor-gas discharge // IOP Conf. Series: Journal of Physics: Conf. Series. Volume 1058 (2018), Article number 012009.
16. Galiev I.G., Khafizov K.A, Khusainov R.K. Increase of efficiency of tractors use in agricultural production // 17th International Scientific Conference Engineering for rural development Proceedings, Volume 17 May 23-25, 2018, pp. 373-377.
17. Khusainov R.N., Khafizov K.A, Nurmiyev A.A., Galiev I.G. Optimization of main parameters of tractor and unit for seeding cereal crops with regards to their impact on crop productivity // 17th
18. Alexandr Belinsky, Bulat Ziganshin, Ayrat Valiev, Damir Haliullin, Ilgiz Galiev. Theoretical investigation of increasing efficiency of combine harvester operation on slopes // 18th International Scientific Conference Engineering for rural development Proceedings, Volume 18 May 22-24, 2019, pp. 206-213.