

Methods to Predict Stresses in Cutting Inserts Brazed Using Iron-Carbon Brazing Alloy

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Abstract. This work describes a method for predicting residual and operating stresses in a flat-form tool insert made of tungsten free carbides brazed using iron-carbon alloy. According to the studies' results it is concluded that the recommendations relating to the limitation of a melting point of tool brazing alloys (950-1100°C according to different data) are connected with a negative impact on tools as a composite made of dissimilar materials rather than on hard alloys as a tool material. Due to the cooling process stresses inevitably occur in the brazed joint of dissimilar materials, and these stresses increase with the higher solidification temperature of the brazing alloy.

1. Introduction

Analytical studies show that about a half of the agricultural machinery failures occur for production reasons. This rate has been maintaining at the same level for the past 15 years. Operation life of complex mechanisms is usually determined by durability of the weakest components and parts.

For example, life of high pressure hoses, composed of high-pressure sleeves and nozzles is determined by durability of sleeve screening braid if careful embedding of nozzles. The service life of internal combustion engines depends on durability of valve springs, specifying the output parameters of engines, namely fuel consumption and capacity.

2. Timeliness of the research

Capabilities of a tool to do its jobs are largely determined by actual defects resulting from deformations caused by manufacturing processes [1]. Pores, any kind of inclusions, structural heterogeneity, grains in different sizes, micro- and macro cracks are the most dangerous defects.

The stresses occurring during the tool making processes and the usage can lead to the following consequences:

- reducing in adhesion of brazing alloys to tool materials;
- deteriorating physical and mechanical properties of brazing alloys and compositions consisting of tool material – braze – tool body;
- forming dangerous internal micro cracks that can cause the destruction of cutting tools while operations.



The known tools, including custom made tools do not meet the requirements in terms of durability, strength and wear resistance. The use of tungsten free hard alloys helps to solve this problem, but the mechanical jointing of such tool inserts due to their low rigidity results in malfunctioning in response to impact and load actions. Brazed cutting tools with tungsten-free carbide inserts are not possible to make using conventional brazing techniques because the contact angle of wetting a brazing alloy on the surface of tungsten-free carbides is low ($<300^\circ$). This leads to the increased tool expenditure, decreased rate of equipment use and higher costs of cutting processes and tool recovery procedures. The demand for quality cutting tools intended for use in repair and reconditioning service for agricultural machinery only in Kemerovo oblast makes 100 thousand units per year, with the tool resistance specified as 45 minutes.

3. Methods of research, authenticity and validity of the results

The simplified and trial techniques and methods as well as the finite element method are used to evaluate residual and operating stresses.

To determine the stresses arising during the tool brazing process we make the following assumptions:

- a brazing alloy is ideally aligned with a tool material, there is no displacement between them;
- brazing alloys and tool materials are anisotropic and obey Hooke's law;
- stresses along the contact length are equal.

Then the total strain can be written as follows:

$$\varepsilon = (\varepsilon_{TC} + \varepsilon_{II}) = \frac{h_{TC} E_{II}}{h_{TC} E_{TC} + h_{II} E_{II}} \quad (1)$$

Where $\varepsilon_{TC} + \varepsilon_{II}$ is the total strain after the brazing process;

h_{TC}, h_{II} are the thicknesses of a carbide insert and brazing alloy respectively;

E_{TC} и E_{II} are the values of the Young's modulus relating to the carbide insert and the brazing alloy respectively.

The mean value of residual stress in the carbide insert can be determined by the following expression

$$\sigma_{O_{TC}} = (\varepsilon_{TC} + \varepsilon_{II}) \frac{h_{TC} E_{II}}{h_{TC} E_{TC} + h_{II} E_{II}} E_{TC} \quad (2)$$

Then

$$\varepsilon_{TC} + \varepsilon_{II} = \frac{P_{TC}}{b h_{TC} E_{TC}} + \frac{P_{II}}{b h_{II} E_{II}} \left(1 + \frac{h_{TC} + h_{II}}{2 \rho_{TC}} \right) + \frac{h_{TC}}{2 \rho_{TC}} + \frac{h_{II}}{2 \rho_{TC}} \left(1 + \frac{h_{TC} + h_{II}}{2 \rho_{TC}} \right) \quad (3)$$

Where P_{TC}, P_{II} are the tensile forces in the x-axis direction;

b is the width of supporting area under the carbide insert;

ρ_{TC}, ρ_{II} are radii of curvature of the carbide insert and the brazing alloy respectively.

And since $P_{TC} = P_{II}$, then we can write the following

$$M_{TC} + M_{II} = \frac{P_{TC}}{2} (h_{TC} + h_{II}) \quad (4)$$

Where M_{TC}, M_{II} are the bending moments of the carbide insert and the brazing alloy respectively.

$$M_{TC} = \frac{E_{TC} J_{TC}}{\rho_{TC}}; \quad M_{II} = \frac{E_{II} J_{II}}{\rho_{II}}, \quad (5)$$

Where J_{TC} , J_{II} are the axial moments of inertia of the carbide insert and the brazing alloy respectively ;

$E_{TC}J_{TC}$, $E_{II}J_{II}$ are stiffness when bending the carbide insert and the brazing alloy respectively.

If $\rho_{TC} = \rho_{II}$, formula (3) can be put in the following form

$$\varepsilon_{TC} + \varepsilon_{II} = \frac{h_{TC}^3 E_{TC} + h_{II}^3 E_{II}}{6\rho h_{TC}(h_{TC} + h_{II})} + \frac{h_{TC}^3 E_{TC} + h_{II}^3 E_{II}}{6\rho h_{II} E_{II}(h_{TC} + h_{II})} + \frac{h_{TC}^3 E_{TC} + h_{II}^3 E_{II}}{12\rho^2 h_{II} E_{II}} + \frac{h_{II} + h_{TC}}{2\rho} \quad (6)$$

By substituting expressions (4) and (5) into (6) we get

$$\sigma_{o_{TC}} = \left[\frac{h_{TC}^3 E_{TC} + h_{II} E_{II}}{6\rho h_{TC}(h_{TC} + h_{II})} + \frac{E_{TC}(h_{TC}^3 E_{TC} + h_{II}^3 E_{II})}{12\rho^2 (h_{II} E_{TC} + h_{II} E_{II})} + \frac{E_{TC} E_{II} h_{II}(h_{TC} + h_{II})}{2\rho(h_{TC} E_{TC} + h_{II} E_{II})} \right] \frac{1}{1 - \mu^2} \quad (7)$$

Where μ is the Poisson's ratio in carbide – brazing alloy composite.

Therefore, the stress in the carbide cutter insert having a flat form is expressed as follows

$$\sigma_{o_{TC}} = \frac{(\alpha_{TC} + \alpha_{II})\Delta T}{\frac{1 - \mu_{TC}}{E_{TC}} + \frac{1 - \mu_{II}}{E_{II}} \cdot \frac{h_{TC}}{h_{II}}} \quad (8)$$

Where α_{TC} , α_{II} are the coefficients of linear expansion of the carbide and brazing materials respectively;

ΔT is the difference between the ambient temperature and the brazing temperature;

μ_{TC} и μ_{II} are the Poisson's ratios for the carbide and the brazing alloy respectively .

Relative to a two-layer cutter insert a unified theory of stiffness is as follows

$$\begin{cases} \sigma_{o1} \leq [\sigma]_p / K_3, & \sigma_{o1} > 0; \\ \sigma_{o2} \leq [\sigma]_- / K_3, & \sigma_{o2} < 0, \end{cases} \quad (9)$$

Where $[\sigma]_p$ and $[\sigma]_-$ are the values of tensile strength of material under tension and compression respectively;

K_3 is the strength factor;

σ_{o1} are the residual stresses in the material having a lesser value α_T ;

σ_{o2} - the same relating to a greater value α_T .

When the thickness of both layers is equal $\sigma_{o1} = -\sigma_{o2}$ and considering $||[\sigma]_p| < |[\sigma]_-|$, then the limiting condition is the first one in (9). In other words, an interlayer crack will be growing in the tool material with a lower coefficient of thermal linear expansion, which has stretching residual stresses. For different layer thicknesses

$$\sigma_{o1} = -\sigma_{o2} h_2 / h_1, \quad (10)$$

Where h_1 and h_2 are the thicknesses of the first and second layer respectively. To calculate the value of residual stresses at their interface we suggest the following formula

$$\sigma_{o1} = (\alpha_{T1} - \alpha_{T2})\Delta T \left/ \left[\frac{1 - \mu_1}{E_1} + \frac{1 - \mu_2}{E_2} \cdot \frac{h_1}{h_2} \right] \right., \quad (11)$$

Where α_{T1}, E_1, μ_1 are the coefficient of thermal expansion, the Young's modulus and the Poisson's ratio relating to the first material;

α_{T2}, E_2, μ_2 are the same relative to the second material;

ΔT is the heating temperature when manufacturing or using the two-layer composite.

With regard to a cutting wedge made of two different anisotropic wedges and having of a flat phase boundary, expression (11) can be written as

$$\sigma_{o1} = (\alpha_{T1} - \alpha_{T2}) \Delta T / \left[\frac{1 - \mu_1}{E_1} + \frac{1 - \mu_2}{E_2} \cdot \frac{\sin(\nu - \gamma)}{\cos(\alpha + \nu)} \right], \quad (12)$$

Where ν is the angle of wedge interface between phases.

Considering (3.4), conditions for crack resistance (10) are as follows

$$(\alpha_{T1} - \alpha_{T2}) \Delta T / \left[\frac{1 - \mu_1}{E_1} + \frac{1 - \mu_2}{E_2} \cdot \frac{\sin(\nu - \gamma)}{\cos(\alpha + \nu)} \right] \leq [\sigma]_p K_3; \quad (13)$$

$$(\alpha_{T1} - \alpha_{T2}) \Delta T / \left[\frac{1 - \mu_1}{E_1} \cdot \frac{\cos(\alpha + \nu)}{\sin(\nu - \gamma)} + \frac{1 - \mu_2}{E_2} \right] \leq [\sigma] K_3.$$

In order to obtain between-group composites, two-component three-layer composites are possible, where the middle layer represents a mixture composed by materials of two other layers. The coefficient of thermal linear expansion α_{TC} and the tensile strength σ_{BC} of the mixture are determined by the rules of mixtures

$$\alpha_{T1} = 100\alpha_{T1}\alpha_{T2} / (P_1\alpha_{T2} + P_2\alpha_{T1}); \quad (14)$$

$$\sigma_{BC} = 100\sigma_{T1}\sigma_{T2} / (P_1\sigma_{T2} + P_2\sigma_{T1}), \quad (15)$$

Where P_1 and P_2 are the material contents in percentage in the mixture.

Based on the analysis of equations (7) and (8) we can make a conclusion that aligning properties of the brazing alloy and the carbide is mainly limited to the maximum reduction of difference in coefficients of linear expansion α_{TC} , α_{II} . However, making these coefficients equal is impossible in practice, for this reason it is required to follow the condition $\alpha_{TC} < \alpha_{II}$ at least. In this case, compressive stresses appear in the carbide insert, and these stresses are less dangerous in terms of brittle fracture occurrence throughout the carbide material and at the interface between the carbide and the braze.

Decreasing the values of E_{TC} , E_{II} and μ_{TC} , μ_{II} parameters results in the reduction of stresses occurring in the carbide and at the interface between the carbide and the brazing alloy, because stiffness of tools and their ability to resist elastic and plastic deformation increase with this.

Especially dangerous are the stresses occurring in carbides when temperatures on tool's contact surfaces sharply change, that is typical for discontinuous cutting processes and cutting where dimensional allowances are varying (in particular along metal deposits). In this case the stresses developing in carbides can be analyzed using the Biot number [6, 7, 8, 10].

$$Bi = \frac{h_{TC}\chi}{2\lambda_{TC}} \quad (16)$$

Where h_{TC} is the thickness of the carbide insert;

χ is the coefficient of heat transfer between the ambient temperature and the tool;

λ_{TC} is the heat conductivity of the carbide.

According to the Biot number the reduction of thermal stresses in a carbide can be achieved by either increasing thermal conductivity of the carbide λ_{TC} the tool body or reducing the carbide insert thickness.

After sintering two-layer composites, compressing stresses occur in materials having a lower coefficient of linear expansion and tension stresses in materials having a higher coefficient. Therefore, the stresses determined by formula (11) must not exceed the compressing stresses for materials with a lesser value α_{TC} . In this case, the tensile strength of materials has been determined by taking into account the safety factor $K3=1.5$. Putting different values of ratios h_1 and h_2 into the formula we can define the stresses in layers.

4. Results of the research

The test results confirmed the researches performed by authors in [2, 3, 7, 8, 11] indicating that the short-run (≈ 45 sec.) and high temperature (about 1180°C) brazing process do not have a negative effect on cutting and strength properties relating to carbides.

A higher melting temperature results in improving the adhesion and diffusion of materials of brazed components exhibiting good wetting and spread properties that is considered a positive factor relative to the refractory quality of brazing alloys. This results from the energy sufficient to activate brazing materials, as it is believed that the thermodynamic activity of elements becomes substantially higher only when $T=2/3T_{\text{пл}}$ relative to the melting points of main components [4,5,9]. At the same time a brazing alloy with a higher melting point largely maintains its strength qualities at increased operating temperatures.

Laboratory tests of carbide alloys for their wear resistance are reported in Figure 1, showing the high rate of running-in wear of the carbide T15K6 h3 up to 0.4 mm in comparison with the carbide KHT16 h3 having the running-in wear within 0.2 ... 0.22 mm, depending on a method used to mount carbide inserts. In the second stage the back surface wear of the KHT16 carbide brazed using a FeC alloy remained almost constant; the rest of test samples showed increased values of wear, especially severe wear was detected in the case of mechanically mounted inserts in the T15K6 alloy.

The highly intensive running-in wear is associated with a defective surface layer of up to 0.1 mm, the presence of which is caused by the interaction of hard alloy surface with air and flux during high temperature heating.

The most preferred variants relating to two-layer inserts are composites with the cutting tip and base materials having the same coefficient of linear expansion, because thermal stresses do not occur in such composites. For this reason the base material is required to be a mixture of materials, with one material having a coefficient of thermal expansion less than the cutting tip material coefficient, and the other – higher (a coefficient of thermal expansion of the mixture was calculated using formula (14)). In this connection there is a need for a low cost material having low α_T , whereas in practice the situation is reversed: the cost of tool materials rises with decreasing α_T and increasing the elastic modulus. Therefore, this methodology can be used when composites have a cutting tip material with minimum α_T being $(4...5) \times 10^{-6} \text{K}^{-1}$.

5 Conclusions

The investigated conditions suggest that the recommendations on limiting a melting temperature of brazing alloys used for tooling (950-1100 °C according to various sources) are connected with a negative impact on the tool as a composite of dissimilar materials, rather than on the carbide as a tool material. Due to the cooling process the stresses inevitably occur in the brazing joint of dissimilar materials, and these stresses increase with the higher solidification temperature of the brazing alloy.

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