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Metal alloys for fasteners of hybrid joints

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The characteristics of metal alloys used for manufacturing fasteners for hybrid joints are considered. Alloys that can be used in the manufacturing embedded elements when creating hybrid joints are recommended as following: alloy steels (30ХГСА, 12Х18Н10Т), aluminum (Д16, В95) and titanium alloys (ВТ1, ВТ5, ВТ6, etc.). The peculiarities of their strengthening heat treatment were analyzed, the influence of polymer binder formation process on the properties of metal elements of transverse or longitudinal joints was considered. Practical recommendations are given on the use of metal alloys as fastening elements of hybrid joints: when creating a hybrid joint for manufacturing embedded elements, it is recommended to use the following alloys – alloy steels (30ХГСА, 12Х18Н10Т), aluminum alloys (D16, B95), titanium alloys (BT1, BT5, BT6 etc.). If the curing temperature of polymer binder is 200 °C and above, then it is recommended to use alloyed steels, titanium alloys as a material for manufacturing transversal or longitudinal joining elements; if the hardening temperature of polymer binder is up to 150 °C, it is recommended to use aluminum alloys as a material for manufacturing transversal or longitudinal joining elements. To improve mechanical properties of alloy steels, aluminum and titanium alloys it is necessary to carry out heat treatment – quenching and tempering for steels; quenching and natural aging or quenching and artificial aging for aluminum alloys; annealing or quenching and artificial aging for titanium alloys. Before the introduction of metal elements into the composite structure, they must be heated to ensure easier penetration of fastening elements into composite.

Keywords: hybrid joints; embedded elements; composite material; heat treatment.

Introduction

Application of composites in the main load-carried structural elements of aircraft is associated with the necessity to develop and implement modern structural and technological solutions (STS) for joining parts made of composites. The class of joints based on rigid connections combines different structural and technological solutions for joints that work at tear out, where a rigid element (for example, needle, pin) acts as a fastening element, i.e. an element that transmits shear force. Such elements are obtained by means of different technological processes including one or more technological operations.

The most promising structural and technological solutions of metal composite heterogeneous structures are structures with transversal joining elements and structures with longitudinal joining elements. Alloyed steels, aluminum and titanium alloys are used for manufacturing metal part of hybrid joints [1].

Purpose and task statement

The purpose of the work is to consider the characteristics of metal alloys used for manufacturing fasteners of hybrid joints. In order to ensure the achievement of this goal, the following tasks were set and solved: the features of strengthening heat treatment of the metal part of a hybrid joint were considered, the influence of the polymer binder formation process on the properties of metal elements for transversal or longitudinal fasteners was analyzed, and practical recommendations were given on the use of metal alloys as fastening elements of the hybrid joints.

Analysis of research results

The advantages of steels are a high modulus of elasticity, relatively low price, and proven operational reliability. Various embedded elements are made of structural medium-alloyed medium-strength steels, strengthened by heat treatment to σ_b = 900…1400 MPa, including welded ones.

The use of steel 30ХГСА for embedded elements is related to its physical-chemical and mechanical properties, manufacturability considering operational conditions: load, contact with other materials, etc. Steel 30ХГСА has high reliability, doesn't require strict adherence to technological regimes, and has a reserve of plastic characteristics. Properties of steel 30ХГСА after annealing are σ_b = 500...750 MPa, δ = 16%, HB = 3000 MPa; after hardening – σ_b = 1100...1300 MPa, δ = 10%, HB = 3100...3600 MPa.

To obtain the required properties, heat treatment is recommended: annealing at 900°C, quenching from the temperature of 900°C in oil with subsequent tempering to the required strength (properties are given in Table 1) [2].

Table 1

Strength of steel 30ХГСА after tempering at different temperatures

Temperature, °C	480-500	520-540	540-560	580-600	620-640	660-680
σ_b, MPa	1200-1400	1100-1300	1000-1200	900-1100	800-1100	700-900

Following chrome-nickel steels are also used for embedded elements: 12Х18Н9, 12Х18Н10Т. To obtain an austenitic structure that provides high corrosion resistance, steel is hardened at a temperature of 1100...1150ºC in water. Although the austenite structure is stable even when cooled in air, cooling in water prevents the release of carbides, which negatively affects corrosion resistance.

Chromium-nickel steels are well spot-welded and stamped. But when hardened steels are heated to the temperatures of 550...750ºC, for example during welding, they become brittle and become prone to intercrystalline corrosion. This is due to the release of $Cr_{23}C_6$ carbides and the depletion of austenite by chromium below the limit that ensures corrosion resistance, i.e. 12.5%.

Steels 12Х18Н9, 12Х18Н10Т are satisfactorily processed by cutting. Steel 12Х17Г9АН4 is well stamped. Properties of steels 12Х18Н9, 12Х18Н10Т, 12Х17Г9АН4 are given in the Table. 2 [2].

Table 2

Properties of steels 12Х18Н10Т 12Х18Н9,12Х17Г9АН4

Steel	State of samples	$\sigma_{0.2}$, MPa	σ_b, MPa	δ, %
12Х18Н10Т	Hardened	200	500	40
12Х18Н9	Hardened	200	520	40
12Х17Г9АН4	Hardened	390	780	65
	Work hardening	950	1130	24
	Highly work hardening	1120	1300	20

Aluminum alloys are characterized by low density, corrosion resistance, and are relatively easily processed by hot and cold deformation, forging, pressing, and sheet stamping. All aluminum alloys can be welded by electric spot welding, and special ones – by melting and other types of welding. Aluminum alloys are easily cut, and protective coatings can be applied to their surface. The complex of physical, mechanical, technological and corrosion properties is determined by the chemical and phase composition, the method of production, and the modes of heat treatment. Thus, the complex of properties of aluminum alloys depends on the stage of aging: zone (T), phase (T1), coagulation (T2, T3).

For example, for the B95 alloy at the T1 stage, maximum strength is achieved with decrease in corrosion resistance, fracture toughness and plasticity. At stages T2, T3, corrosion resistance is significantly increased, an optimal ratio of the characteristics of strength, fracture toughness and plasticity is ensured.

Alloy Д16 in hardened and naturally aged states (T) combines well characteristics of endurance, fracture toughness, and resistance to fatigue crack propagation. In the T1 state (hardened and artificially aged), these indicators are 1.5…2 times higher. For duralumin (Д16), the following heat treatment modes are recommended: M – annealing – heating to t = 350 - 370 °C, exposure for 2-4 hours; T – hardening with t = 495 - 505 °C, natural aging within 24 - 96 hours; T1 – hardening with t = 495 - 505 °C, artificial aging at t = 130 - 180 °C for 6 - 20 hours.

The mechanical properties of aluminum alloys after different types of heat treatment are given in Tables 3 - 4 [2, 3].

Table 3

Tensile mechanical properties of alloy Д16

State of samples	σ_b , MPa	$\sigma_{0.2}$, MPa	δ_{10} , %
Annealing	145 - 235	-	10
Hardening and natural aging	405 - 425	270 - 275	10 - 13
Hardening, natural aging, work hardening	425 - 455	335 - 345	8 - 10

Alloys B95, B95оч, B95пч have high strength characteristics in comparison with the main structural aluminum alloys. The maximum strength is achieved after hardening and artificial aging according to the T1 mode. In the T2 and T3 states, the strength characteristics of the alloys are lower by 7-10% and 12-15%, respectively, than in the T1 state.

Table 4

Tensile mechanical properties of B95 alloy

State of samples	σ_b, MPa	$\sigma_{0.2}$, MPa	δ_{10} , %
Annealing	245	-	10
Hardening and artificial aging	480-490	390-410	6-7

For high-strength aluminum alloys (B95), the following heat treatment modes are recommended: M – annealing – heating to t = 290 - 390 °C, exposure for 2-4 hours; T1 – hardening with t = 465 - 475 °C, artificial aging at t = 115 - 125 C for 23 - 24 hours ; T2 – hardening with t = 465 - 475 °C, artificial aging at t = 110 – 120 °C for 5 - 10 hours + artificial aging at t = 160 - 170 °C for 14 - 18 hours; T3 – hardening with t = 465 - 475 °C, artificial aging at t = 110 - 120 °C for 5 - 10 hours + artificial aging at t = 160

- 170 °C for 25 - 35 hours.

Titanium alloys, due to their physical, mechanical and chemical properties, are unique materials for many industries, in particular, aerospace. High-strength titanium alloys include thermally strengthened alloys, the high strength of which is achieved by quenching and aging. Such alloys, both in the annealed and thermally strengthened states, can successfully and for a long-time work in aerospace structures at temperatures up to 400 °C. Modes of strengthening heat treatment and mechanical properties of titanium alloys are given in Tables 5-6 [2].

Table 5

Effect of heat treatment on the properties of titanium alloys BT22, BT3-1, BT14

Alloy	Heat treatment	Mechanical properties		
		σ_b , MPa	$\sigma_{0.2}$, MPa	δ,%
BT22	annealing 750 °C, cooling in the furnace to 350 °C	1080	1000	-
	quenching 750 °C, aging 500 °C	1480	-	5.3
	quenching 750 °C, aging 550 °C	1345	-	3.7
BT3-1	annealing 750 °C	880	800	-
	quenching 920 °C	1140	680	12.8
	quenching 920 °C, aging 520 °C	1510	-	3.1
BT14	annealing 750 °C, cooling in air	1080	1040	-
	quenching 880 °C , aging 480 °C	1370	1275	5
	quenching 880 °C, aging 510 °C	1060	1010	12.5

Table 6

Mechanical properties of alloys BT6, BT16, BT3-1, BT22
after various types of heat treatment depending on the testing temperature

Alloy	State of samples	T_{test}, °C	E, GPa	$\sigma_{0.2}$, MPa	σ_b, MPa	δ, %	ψ, %
BT6	Annealed	20	125	900	1000	10	30
	Hardened and aged	20	125	1050	1150	8	30
		350	102	720	860	8	45
		400	101	600	820	9	50
BT16	Annealed	20	105	800	850	22	65
	Hardened and aged	20	112	1170	1350	8	40
		300	92	830	1080	9	27
		450	82	830	1070	9	20
BT3-1	Annealed	-40	-	1070	1120	12	35
		20	115	930	1000	10	30
		100	113	820	950	10	45
		400	100	630	800	8	55
BT22	Annealed	-70	-	-	1250-1350	5-10	20-40
		20	110	1050-1150	1100-1250	10-16	35-50
		300	95	800-850	900-950	8-16	35-60
		400	85	700-750	800-900	10-18	40-65

The process of curing polymer composite with elements of transversal or longitudinal fasteners takes place when heated to an average temperature of 120…250 °C for 1 - 4 hours. Therefore, it is important to consider the influence of polymeric composites curing regimes on the properties of alloy steels, titanium and aluminum alloys from which transverse or longitudinal joining elements are made.

After analyzing changes in the mechanical properties of titanium alloys (ВТ6, ВТ16, ВТ3-1, ВТ22), aluminum alloys (Д16, В95) and alloyed steels (30ХГСНМА, 40ХН2ВА, 20Х13, 07Х16Н6) under the action of high temperatures, the following conclusions can be drawn:

- for specimens from Д16 at a temperature of 150 °C decreasing of σ_b by 6 - 12%, $\sigma_{0,2}$ by 2 - 12% is observed; at a temperature of 200 °C – σ_b decreases by 16 - 24 %, $\sigma_{0.2}$ – by 11 - 22%, and more strengthening is observed for work hardened specimens; for В95 specimens at t = 150 °C σ_b decreases by 15 - 22%, and t = 200 °C – by 36 - 40%, $\sigma_{0.2}$ at t = 150 °C – by 12 - 18%, and at t = 200 °C σ_b – by 30 - 38%, and more strengthening is observed for heat-treated specimens according to the T2 mode; there is decreasing in the strength limit by 22%, yield limit by 18 - 22% for specimens made of high-strength В95 alloy (thickness 2 mm) at a temperature of 150 °C; there is a decreasing in the strength limit by 28%, the yield limit by 45 – 46 %at a temperature of 200 °C; there is a decrease in the strength limit by 11%, yield limit by 7% for specimens made of steel 20Х13 at a temperature of 200 °C;

- for specimens made of steel 40ХН2ВА at a temperature of 250 °C decreasing in the strength limit by 6%, yield limit by 12% is observed; there is no decreasing in the strength limit, but the impact toughness decreases by 2 - 8% for specimens made of 30ХГСНМА steel at temperatures of 250-300 °C; for specimens made of steel 07Х16Н6 a slight decreasing in strength characteristics is observed at temperature of 450 °C – strength limit by 3%, yield limit by 5%;

- for specimens made of titanium alloy ВТ3-1 at a temperature of 100 °C decreasing in the strength limit by 5%, yield limit by 12% is observed; for specimens made of titanium alloy ВТ6 at temperatures of 350 °C decreasing in the strength limit by 25%, yield limit by 31% is observed; for specimens made of titanium alloy ВТ16 decreasing of strength limit by 20%, yield limit by 29% is observed at a temperature of 300 °C; for specimens made of titanium alloy ВТ22 decreasing in the strength limit by 18%, yield limit by 24% is observed at temperatures of 300 °C [2].

Thus, the temperatures of polymer binder curing during the manufacture of metal composite heterogeneous structures don’t change the mechanical properties of steels 30ХГСНМА, 07Х16Н6 and lead to insignificant decreasing in the mechanical properties of steels 20Х13, 40ХН2ВА and titanium alloys ВТ6, ВТ16, ВТ3-1, ВТ22. Conversely, the mechanical properties of aluminum alloys Д16, В95 significantly decrease at curing temperatures, especially at temperatures of 200 - 250 °C.

Conclusions

Recommendations concerning the application of metal alloys for fasteners of hybrid joints:

- when creating a hybrid joint for the manufacture of embedded elements it is recommended to use the following alloys – alloyed steels (30ХГСА, 12Х18Н10Т), aluminum alloys (D16, В95), titanium alloys (ВТ1, ВТ5, ВТ6, etc.);

- to improve the mechanical properties of the above alloys it is necessary to carry out heat treatment;

- if the curing temperature of polymer binder is 200 °C and above, then it is recommended to use alloyed steels, titanium alloys as a material for the manufacturing of transversal or longitudinal joining elements; if the hardening temperature of the polymer binder is up to 150 °C it is recommended to use aluminum alloys as a material for the manufacturing of transversal or longitudinal joining elements.
- before the introduction of metal elements into the composite structure, they must be heated to ensure easier penetration of the elements into the composite.

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Металеві сплави для кріпильних елементів гібридних з'єднань

Розглянуто характеристики металевих сплавів які використовують для виготовлення кріпильних елементів гібридного з’єднання. Рекомендовано сплави, що можуть бути використані при виготовленні закладних елементів при створенні гібрідного з’єднання: леговані сталі (30ХГСА, 12Х18Н10Т), алюмінієві (Д16, В95) та титанові сплави(ВТ1, ВТ5, ВТ6 та ін.). Проаналізовано особливості їх зміцнюючої термічної обробки. Розглянуто вплив процесу формування полімерного сполучного на властивості металевих елементів поперечного або поздовжнього зв’язку. Наведено практичні рекомендації щодо застосування металевих сплавів в якості кріпильних елементів гібридного з′єднання: при створенні гібридного з′єднання для виготовлення закладних елементів рекомендується використовувати наступні сплави – леговані сталі (30ХГСА, 12Х18Н10Т), алюмінієві сплави (Д16, В95), титанові сплави (ВТ1, ВТ5, ВТ6 та ін.). Якщо температура твердіння полімерного сполучного 200°С та вище тоді в якості матеріалу для виготовлення елементів поперечного або поздовжнього зв’язку рекомендується використовувати леговані сталі, титанові сплави; якщо температури твердіння полімерного сполучного до 150°С – в якості матеріалу для виготовлення елементів поперечного або поздовжнього зв’язку рекомендується використовувати алюмінієві сплави. Для покращення механічних властивостей легованих сталей, алюмінієвих та титанових сплавів необхідно проводити термічну обробку – гартування та відпуск для сталей; гартування та природне старіння або гартування та штучне старіння для алюмінієвих сплавів; відпал або гартування та штучне старіння для титанових сплавів. Перед впровадженням металевих елементів в композитну конструкцію їх необхідно нагріти, щоб забезпечити більш вільне проникнення елементів у композит.

Ключові слова: гібридне з’єднання; закладні елементи; композиційний матеріал; термічна обробка.

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