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EFFECTS OF COMPOSITION AND STRUCTURE ON THE STATE, FATIGUE, AND DAMPING PROPERTIES OF HIGH-STRENGTH CAST IRON

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Measurements have been made on the ultimate strength, yield stress, endurance limit with and without stress concentrators, and oscillation decrement for cast iron containing spheroidal graphite and alloyed (in mass %) with 0.30-1.08 Mn, 0-0.81 Cu, 0.45-0.62 Ni, and 0-0.32 Mo and having structures of ferrite, pearlite, bainite, and bainite-ferrite types (with 25-30% ferrite) and also martensite structure. Concentrations of those elements have been determined that provide the best combination of static and dynamic characteristics. The effects of the alloying elements on the properties of the cast iron have been related to the structure of the metal substrate. In particular, in pearlitic cast iron alloyed with 0.7-0.8% Cu, 0.4-0.5% Ni, 0.3% Mn, the addition of Mo is ineffective, while in cast iron having the bainite structure, that element raises the yield stress and the fatigue strength even in the absence of Cu, while the sensitivity to stress concentration is reduced.

We have examined the static and fatigue strength as well as the damping capacity for several forms of cast iron having pearlite and bainite structures in order to choose the best composition and structure for high-strength cast iron containing spheroidal graphite in order to provide sufficient working life in highly stressed components (crankshafts, distribution shafts, and so on) operated under conditions of intensive cyclic loading. The main viability parameters for such cast iron under alternating loads are the yield strength, endurance limit, stress concentration coefficient, and oscillation decrement. These characteristics are independent but are often correlated. For example, the endurance limit is directly related to the yield strength, while the level of the latter is definitely related to the capacity of the material to damp vibrations. High damping capacity is responsible for reducing the vibration amplitude and the stress peaks, which reduces the danger of fatigue failure, since such failure and irreversible energy dissipation in a polycrystalline material are related to plastic strain in microvolumes [1, 2].

TABLE 1. Cast-Iron Compositions

Composition type	Alloying-element contents, mass %			
	Mn	Cu	Ni	Mo
1	0,30	0,81	0,46	—
2	0,30	0,74	0,45	0,28
3	0,54	—	0,49	0,32
4	0,57	0,70	0,62	—
5	1,08	0,68	0,60	—

Note. The cast iron also contained the following in mass %: 3.6-3.8 C; 2.6-2.9 Si, up to 0.06 Cr, and up to 0.06 P; 0.04-0.06 Mg; 0.008-0.013 S.

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TABLE 2. Static and Fatigue Properties of Cast Irons

Characteristic	Matrix structure	Composition type from Table 1				
		1	2	3	4	5
σ_u, MPa	F	—	—	492	—	—
	P	830	830	645	800	830
	B	1305	1220	1180	1130	1210
	BF	—	—	785	—	—
	M	—	—	980	—	—
$\sigma_{0,2}$, MPa	F	—	—	345	—	—
	P	550	570	440	590	585
	B	810	880	860	890	900
	BF	—	—	545	—	—
	M	—	—	730	—	—
σ_{-1}, MPa	F	—	—	175	—	—
	P	290	300	265	280	260
	B	375	355	390	360	330
	BF	—	—	335	—	—
σ_{-1}^n MPa	F	—	—	115	—	—
	P	195	200	165	185	165
	B	225	200	240	245	220
	BF	—	—	215	—	—
K	F	—	—	1,52	—	—
	P	1,49	1,50	1,61	1,51	1,58
	B	1,67	1,88	1,60	1,47	1,50
	BF	—	—	1,56	—	—

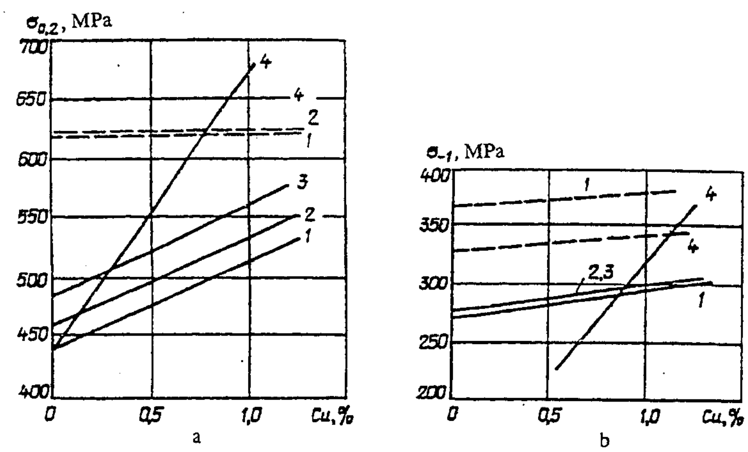

Fig. 1. Effects of Cu, Mn, and Ni on the yield point (a) and endurance limit (b) of cast iron with pearlite structure (solid lines) or bainite structure (dashed lines): 1) 0.3% Mn; 2) 0.3% Mn, 0.5% Ni; 3) 0.3% Mn, 1.0% Ni; 4) 1.0% Mn.

Cast iron has a heterogeneous structure due to inclusions of graphite, which act as local stress concentrators, and this is an independent factor in damping vibrations. If the graphite is spheroidal and the crystallization conditions are identical, the decisive effect on the damping level and other reliability parameters comes from the composition and the structure [3, 4].

We used cast irons alloyed with manganese, copper, nickel, and molybdenum (Table 1) made by the use of modifiers based on magnesium, silicon, and iron type FSMg (TU 14-5-134-86).

The initial cast iron was melted in an electric furnace by standard techniques [5] and was treated in the bucket with the modifier, which was mixed wit the alloying and compensating components. Standard wedge samples were cast, from which blanks were cut for mechanical test. These were first given heat treatment under conditions that provided the following structures: ferrite F, pearlite P, bainite B, bainite–ferrite BF, 25-30% F, and martensite M. The degree of spheroidization in the graphite in these cast irons on the IPL scale [4] was 88-97%, so that factor did not affect the properties.

The fatigue strength was examined* on bending smooth specimens 8 mm in diameter with a given hazardous section (radius of curvature 30 mm, theoretical concentration coefficient $\alpha = 1.04$) and specimens with circular notches (radius of curvature at bottom of notch 1 mm, $\alpha = 1.9$) [6]. The specimens were tested on an MIP-8M machine [7] by loading with a symmetrical cycle at 3000 cycles/min. The test basis was $N = 10^7$ cycles. The fatigue curves $\sigma = f(\log N)$ were processed

*Tests performed by O. Yu. Kramarenko and O. V. Kulikovskaya.

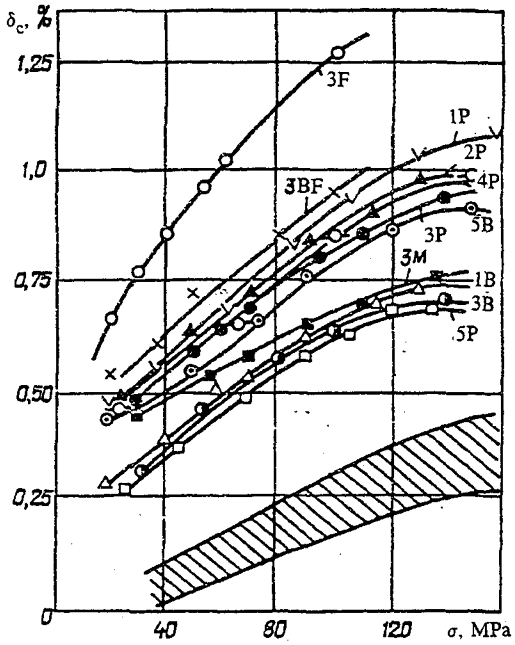

Fig. 2. Amplitude dependence of decrement for cast iron and U8 steel (hatched region), the numbers on the curves corresponding to the composition types in Table 1.

to define the endurance limits of the smooth specimens σ_{-1} and the notched ones σ_{-1}^{n}, together with the effective stress concentration coefficient $K = \sigma_{-1}/\sigma_{-1}^{n}$.

Table 2 gives the static and fatigue characteristic (σ_u and $\sigma_{0.2}$ are respectively the ultimate strength and yield point in tension).

It is evident for type 3 cast iron that the highest values for the ultimate strength, yield point, and endurance occur wit the bainite structure. The bainite–ferrite one is inferior in static strength by 40-50% and in fatigue strength by 10-15%.

The contents of manganese, copper, and nickel were chosen from special tests, which gave the following regression equations: for the pearlite structure

$$\sigma_{0,2}\ (\text{MPa}) = 440 + 78\ \text{Ni} + 234\ \text{MnCu} - 93\ \text{MnNi},\ R = 0{,}751;$$

$$\sigma_{-1}\ (\text{MPa}) = 339 - 53\ \text{Cu} - 217\ \text{Mn} - 6{,}9\ \text{Ni} + 246\ \text{MnCu} + 24\ \text{MnNi},$$

$$R = 0{,}999;$$

$$K = -\ 0{,}49 + 2{,}91\ \text{Cu} + 6{,}38\ \text{Mn} + 0{,}07\ \text{Ni} - 9{,}47\ \text{MnCu} + 0{,}18\ \text{MnNi},$$

$$R = 0{,}796;$$

for the bainite structure

$$\sigma_{0,2}\ (\text{MPa}) = 604 + 46\ \text{Mn} + 412\ \text{Ni},\ R = 0{,}975;$$

$$\sigma_{-1}\ (\text{MPa}) = 385 - 57\ \text{Mn} + 9{,}2\ \text{Cu},\ R = 0{,}998;$$

$$K = 2{,}05 + 0{,}17\ \text{Cu} - 1{,}11\ \text{Ni},\ R = 0{,}994$$

(R is the multiple correlation coefficient).

These equations correspond to the properties of cast irons having 0.26-1.08% Mn; 0-1.28% Cu; 0-1.12% Ni. The graphs from them (Fig. 1) give quantitative evaluation of the static and fatigue strengths in separate and combined alloying.

TABLE 3. Effects of Cyclic Stress Level on Damping Capacity of Spheroidal Graphite Cast Iron in Relation to Matrix Structure

Matrix structure	Decrement δ_c for stress amplitude σ in MPa				
	40	80	120	$0,1\sigma_{0,2}$	$0,2\sigma_{0,2}$
Ferrite	0,85	1,13	1,32	0,81	1,06
Pearlite	0,54	0,75	0,88	0,58	0,78
Bainite	0,37	0,53	0,68	0,59	0,75
Bainite−ferrite	0,64	0,83	0,98	0,72	0,97
Martensite	0,48	0,63	0,72	0,58	0,77

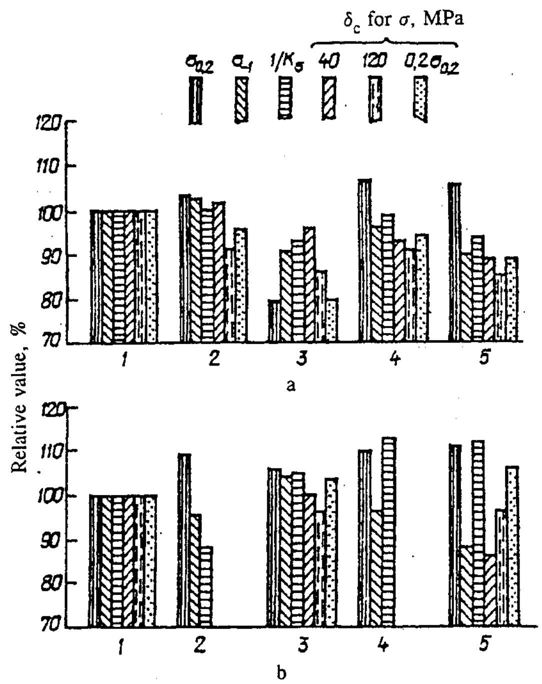

Fig. 3. Comparative diagram for strength parameters and damping capacity in cast iron compositions having the pearlite structure (a) and bainite structure (b). The numbers on the abscissa are the compositions in Table 1.

The damping capacity was examined on flat specimens vibrating in pure bending [3] with an electromagnetically excited apparatus [8]. The maximum stress amplitudes were 20-160 MPa. Figure 2 shows the dependence of the decrement δ_c on the amplitude of the cyclic stresses for these cast irons. For comparison, we give data for steels with similar alloying-element contents.

The damping capacity tends to increase wit the stress amplitude, particularly in the iron with the ferrite structure, since the yield point is the lowest for that structure, which facilitates microplastic deformation around the graphite inclusions. However, the advantage of the ferrite structure is most prominent when one compares decrements corresponding to identical stress amplitudes. Under these conditions, the cast iron with the bainite−ferrite structure exceeds those with pearlite and martensite structures as regards damping, while the least decrement occurs with the bainite structure. The damping capacity of the cast iron having the martensite structure is higher than that in the bainite one because there are higher stress peaks at the edges of the martensite needles [3]. This relation between the decrements alters however when one compared them not for identical absolute stress levels but for stresses proportional to the yield point of the material, i.e., on the basis of the closeness of those stresses to the endurance limit. This is necessary because it is possible to raise the stress intensity, including for cyclic stresses, by using materials with high values for the static and fatigue strength while retaining the same level of strength margin coefficient for the material in the construction.

Table 3 gives the decrement for the type 3 cast iron (Table 1) with various cyclic loads for all the different structures. We conclude that while for example the difference in the decrements for the pearlite and bainite structures is about

50% at 40 MPa, when the stress amplitude is increased to 120 MPa, this difference is reduced to 30%, and at stresses corresponding to 0.1-0.2 of the yield point (which are 0.17-0.33 and 0.22-0.44 of the endurance limits respectively for materials with the pearlite and bainite structures), those cast irons hardly differ in damping capacity and only 25-30% inferior to ones having the bainite-ferrite or ferrite structures.

The amplitude dependence of the decrement for the various compositions (Fig. 2) shows that the best for the pearlite and bainite structures are alloying with copper and nickel but with reduced manganese contents and without molybdenum. This is due to features of the substructure indicated by electron microscopy (magnification × 12,000) from the phase structure [9]. The addition of copper to low-manganese cast iron favors the formation of a cementite component of the pearlite mainly as separated and isolated platelets with elevated dispersion, which during cyclic strain increase the number of microperturbed areas and favor the increase in damping characteristic. The dispersion of the pearlite is reduced when the manganese content is increased, and the continuity of the cementite platelets is increased, which adversely affects the decrement level.

These results confirm the direct relationship we [3, 4] and others have previously found between the damping capacity and the plasticity, which is related to the composition of the cast iron.

Figure 3 shows the relative dynamic strength and yield point of these cast iron compositions having the pearlite and bainite structures, where 100% has been taken as the values for cast iron containing 0.3% Mn; 0.8% Cu and 0.46% Ni (composition 1 in Table 1). Low-manganese cast irons of similar composition provide high strength parameters when combined modifiers are used [10] in both static and cyclic loading states for cast components, and identical results have been obtained in tests on specimens and directly on working components: automobile crankshafts.

Figure 3 enables one to evaluate the level of each of these properties in relation to the alloying-element contents. The pearlite structure is preferable on all the properties for compositions 1 and 2 having low manganese content (0.3%) as alloyed with 0.7-0.8% copper and 0.4-0.5% nickel, and also with up to 0.3% molybdenum. The last does not alter the sensitivity to stress concentration but raises the yield point by 4-5% and the endurance limit by 3%, while reducing the damping capacity at high stress amplitudes. If copper is eliminated and the manganese content is raised to 0.5-0.6% in the pearlitic cast iron (composition 3), all the characteristics deteriorate, particularly the yield point at high load, with the falls in the properties respectively 20, 10, and 15%. With the same manganese content (0.5-0.6%), cast iron alloyed wit 0.7% copper and about 0.6% nickel (composition 4) has higher values for the properties than does the cast iron without copper. The yield point and damping capacity of this cast iron are identical to those in composition 2, although the former is inferior to the latter by 8-10% in endurance limit. If the manganese content is increased from 0.5-0.6% to 1.0-1.1% in cast iron having otherwise the composition 4, all the characteristics are reduced by 4-6%, apart from the yield point, which is virtually unaltered.

For cast iron with the bainite structure, other relations apply between the characteristics as dependent on the alloying-element concentrations. On the set of properties, the best results were obtained wit compositions 1 and 3, where the bainite structure reduced the sensitivity to stress concentration by 10-15% when the manganese content was increased from 0.3 to 1.1% in iron alloyed with 0.7-0.8% copper and 0.4-0.6% nickel (compositions 1, 4, and 5). Adding up to 0.3% molybdenum raised the yield point of the cast iron with the bainite structure by 6-12%, as with increasing the manganese concentration within the above limits.

These mechanical characteristics affecting the reliability of highly stressed spheroidal cast iron components during use enable one to determine the effects from the concentrations of the main alloying elements and the structure of the material on the endurance limit, sensitivity to stress concentration, and damping capacity. We have determined the concentrations of manganese, copper, nickel, and molybdenum that provide the best combination of static and dynamic characteristics. The pearlite structure produces a cast iron containing 0.7-0.8% copper and 0.4-0.5% molybdenum is largely ineffective as regards the combination of properties, while raising the manganese content to 1.1% reduces all the strength characteristics. With the bainite structure and 0.5-0.6% Mn and 0.3% Mo, the yield point and the fatigue strength are raised even in the absence of copper in conjunction with a lower stress concentration coefficient. This bainite cast iron shows reduction in the endurance limit with simultaneous reduction in the sensitivity to notches when the manganese content is increased.

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