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The impact fatigue properties of iron and steel

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Abstract

When a specimen or component is subjected to repeated impacts it may develop a crack or cracks and eventually fracture. It is then said to have failed by impact fatigue. The strain-rate involved in impact fatigue is about $10^3\,s^{-1}$ which is substantially higher than the strain-rate usually used in a conventional fatigue or tensile test. Because of this, an iron or steel specimen undergoing impact fatigue has an unusually high ultimate tensile strength and ductile–brittle transition temperature. This can explain some of the main features of impact fatigue behavior such as the high endurance relative to conventional fatigue for a given stress level, and the tendency to exhibit cleavage rather than a ductile fracture mode. Impact fatigue characteristics may be enhanced by surface hardening techniques such as carburizing, nitriding and steel shot bombardment. The effects of corrosive environments on impact fatigue have not yet been explored.

1. Introduction

When a specimen or component is subjected to repeated impacts it may develop one or more cracks and eventually break into pieces. It is then said to have failed by impact fatigue. In the 1830s axle and bridge failures occurring on the newly developing railroads began to be a problem and Queen Victoria appointed a commission to look into it. In an appendix to the commissions report Eaton Hodgkinson reported the results of both fatigue and impact fatigue experiments on iron [1].

In 1908, Stanton and Bairstow of the National Physical Laboratory in Teddington, England, published the results of an extensive study of impact fatigue in pearlitic plain carbon steels [2]. It remains the most extensive study of impact fatigue ever published. They used eight steels whose carbon contents ranged from 0.039% to 0.604% and silicon contents ranged from “a trace” to 0.040%. Thus, these materials had much lower silicon contents than modern steels. Their specimens were similar to threaded and notched tensile specimens but they were laid horizontally and impacted at the notch by a falling tup. The specimen was rotated 180° about a horizontal axis between successive impacts. The energy absorbed per impact was calculated from the initial height of the tup, the height to which it rebounded, and its weight.

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When Stanton and Bairstow plotted the energy absorbed per impact, E_i, against the number of impacts to failure, N_f, the resulting E_i–N_f curves were found to be similar in shape to conventional S–N curves obtained in fatigue experiments. There was an impact fatigue limit, E_0, for each material. Similar results on a variety of plain carbon alloy steels were reported by McAdam in 1923 [3] using both notched and unnotched specimens. In 1935, Hankins and Mills [4] continued the work of Stanton and Bairstow using unnotched specimens of spring steels.

Johnson and Keller [5] and Johnson and Johnson [6] have used Stanton and Bairstow's results to develop a phenomenological model of impact fatigue for the pearlitic plain carbon steels which Stanton and Bairstow used. They have shown that high cycle impact fatigue is governed by the equation:

$$E_i = E_0 + E_k N_f^{-p}, \tag{1}$$

where E_k and p are known as the impact fatigue parameter and impact fatigue exponent, respectively. They are constant from steel to steel and p has a value of 0.6.

For low cycle fatigue E_i and E_0 are related by the equation

$$E_i = E_0 + mN_f^{-q}, \tag{2}$$

where E_0, m and q all vary from one steel to another. It is found empirically that m and q are related by the equation:

$$q = C \log_e m + D, \tag{3}$$

where C and D are constants. Combining Eqs. (2) and (3) then gives

$$E_i = E_0 + \exp\left(\frac{q-D}{C}\right) N_f^{-q} \tag{4}$$

as the equation governing low cycle impact fatigue. Unfortunately Stanton and Bairstow's steels contained much less silicon than is contained by modern steels. We shall therefore not know whether these equations apply to modern steels until Stanton and Bairstow's work is repeated using such steels.

2. Testing equipment

Since the early work of Stanton and Bairstow, McAdam, and Hankins and Mills, some workers studying impact fatigue have continued to use impacts from a falling tup. Kishimoto et al. [7] have used a falling cylinder impacting precracked specimens. Taira et al. [8] and Iguchi et al. [9] have used a falling hammer with enhanced acceleration provided by a coil spring. A number of workers have developed and used testing machines which employ repeated tensile impacts [10–15]. Others have used the Hopkinson split bar technique [16–18]. A completely different kind of impact fatigue test is one developed and patented for grinding balls [19] and used for testing improved materials for use in these balls [20,21].

These testing methods are quite diverse and so, in general, work on impact fatigue at one laboratory cannot be compared directly with work at another. Each laboratory has tended to focus on studying the effects of varying one or more variables such as composition or heat treatment using a machine it has developed and has done so successfully. There is clearly a need for some organization such as the American Society for Testing and Materials (ASTM) to try to establish a standard impact fatigue test for iron and steel using standard specimens. The field will move forward much faster when this has happened.

3. Materials studied

The present authors have carried out a fairly extensive search of the literature looking for papers on impact fatigue in irons and steels. No claim is made for the completeness of this search, but it has been extensive enough to give a good picture of the present state of our knowledge of this topic. It has focused on work published during or since the 1960s since this material is accessible through computer data bases. Work on 17

Table 1
Studies of the impact fatigue behavior of plain carbon steels reported in the literature

Specification	Composition						Authors	Ref.
	C	Mn	Si	S	P	Other		
S25C	0.25	0.47	0.28	—	—	—Owadano et al.	Owadano et al.	[22]
S45C	0.46	0.24	0.76	0.017	0.024	Ni 0.02 Cu 0.01 Cr 0.11	Kishimoto et al.	[7]
S10C	0.11	0.50	0.25	0.007	0.017	—	Okabe et al.	[14]
S20C	0.20	0.52	0.21	0.013	0.018	—	Okabe et al.	[14]
S35C	0.36	0.58	0.29	0.032	0.025	—	Okabe et al.	[14]
S45C	0.48	0.67	0.23	0.007	0.020	—	Okabe et al.	[14]
S38C	0.39	0.75	0.19	—	—	—	Matsumure et al.	[23]
STY80	0.63	0.62	0.30	—	—	—	Matsumure et al.	[23]
SS41	0.14	0.46	0.18	0.024	0.013	—	Akizono and Murakami	[24]
YM50	0.11	0.95	0.54	0.014	0.011	—	Akizono and Murakami	[24]
S15CK	0.15	0.47	0.27	—	—	—	Furukawa et al.	[25]
S25C	0.26	0.45	0.26	—	—	—	Furukawa et al.	[25]
S38C	0.36	0.74	0.26	—	—	—	Furukawa et al.	[25]
S55C	0.56	0.83	0.26	—	—	—	Furukawa et al.	[25]
S20C	0.21	0.47	0.24	0.021	0.024	—	Taira et al.	[12]
—	0.01	0.38	0.22	0.031	0.018	—	Zhang et al.	[18]
—	—	—	—	—	—	—	Cheng et al.	[26]
CH10A	0.097	0.47	0.009	0.017	0.011	Sol. Al 0.028	Nakayama et al.	[27]

irons or low carbon steels was found. The carbon contents of these materials ranged from 0.01% to 0.63%.[1] They are listed, with their compositions, the authors who studied them, and the numbers of the references given to them at the end of the paper, in Table 1.

Much of the published work on impact fatigue is on alloy steels. Work on a total of 41 such steels was found. These are all listed in Table 2. Most are Ni–Cr, Cr–Mo or Ni–Cr–Mo steels. Table 3 lists 14 other miscellaneous materials which have been studied. These include six cast irons, two maraging steels, an austenitic high manganese steel, an austenitic stainless steel, a two-phase bainitic and martensitic die steel, and two materials described as "semi-steels", one of which was modified by the addition of rare-earth elements. Refs. [22–27] are listed in Table 1, Refs. [28–38] in Table 2, and Refs. [39–45] in Table 3.

4. Characteristics of impact fatigue

The published work on the impact fatigue properties of irons and steels does not yet give a comprehensive picture of the field. Looking at it as a whole one can, however, discern some significant features.

4.1. Heat treatment

Many of the published studies describe work on quenched and tempered alloy steels. Yarema and Kharish [15] working with a Ni–Cr low alloy steel found that there is an optimum tempering temperature of 250 °C for maximizing fatigue life. The crack initiation time and the ultimate tensile strength peak at about the same temperature. In another study on Ni–Cr alloys Molchanov and Klimov [33] found that tempering in the range 220–240 °C gave better results than tempering in the range 180–200 °C, a result consistent with Yarema and Kharish's work.

The retained austenite which forms on quenching alloys with higher amounts of alloying elements has an effect on impact fatigue properties. Kozyrev and Toporov [30] worked with a tool steel containing 1.48% carbon and 11.5% chromium. They concluded that at high stress levels retained austenite improves impact fatigue resistance, but that at low stresses the reverse is true. Pestov et al. [44] produced retained austenite in

[1]All compositions given in this paper are in wt%.

Table 2
Studies of the impact fatigue behavior of alloy steels reported in the literature

Specs.	Composition									Other	Authors	Ref.
	C	Mn	Si	S	P	Ni	Cr	Mo	Cu			
4118	0.19	0.18	0.29	0.024	0.010	0.24	0.47	0.14	—	—	DePaul	[28]
4626	0.29	0.52	0.26	0.020	0.015	0.90	0.10	0.19	—	—	DePaul	[28]
4620	0.18	0.54	0.24	0.012	0.012	1.69	0.15	0.23	—	—	DePaul	[28]
4817	0.18	0.49	0.28	0.014	0.010	3.38	0.06	0.24	—	—	DePaul	[28]
—	0.18	0.44	0.28	0.014	0.010	3.38	0.06	0.24	—	—	DePaul	[28]
16MnCr5	0.20	1.22	0.30	0.039	0.020	0.14	0.97	0.06	—	—	DePaul	[28]
30CrMnSiNiA	0.29	1.08	1.09	0.07	0.015	1.5	1.04	—	0.2	—	Yarema and Kharish	[15]
—	0.14	0.80	0.28	—	—	0.2	1.26	0.47	—	B0.003	Shul'ginov and Matveyev	[29]
—	0.09	1.55	0.20	—	—	0.2	0.25	—	—	—	Shul'ginov and Matveyev	[29]
—	0.13	0.80	0.45	—	—	1.3	0.35	0.15	—	—	Shul'ginov and Matveyev	[29]
Kh12M	1.48	0.3	0.27	—	—	—	11.5	—	—	V 0.2%	Kozyrev and Toporov	[30]
300M	0.4	0.7	1.6	—	—	1.8	0.85	0.4	—	—	Yang and Zhao	[31]
AF1410	0.16	—	—	—	—	10	2	1	—	Co 14 V 0.1	Yang and Zhao	[31]
—	0.20	0.88	0.28	0.022	0.017	—	0.52	0.25	—	Al 0.073	Diesburg et al.	[32]
8620	0.19	0.82	0.27	0.023	0.016	0.50	0.63	0.22	—	Al 0.068	Diesburg et al.	[32]
4620	0.20	0.62	0.23	0.022	0.016	1.78	—	0.25	—	Al 0.079	Diesburg et al.	[32]
4620 + Mo	0.20	0.62	0.23	0.022	0.016	1.78	—	0.49	—	Al 0.056	Diesburg et al.	[32]
—	0.20	0.89	0.27	0.022	0.96	0.55	0.59	0.35	—	Al 0.079	Diesburg et al.	[32]
4320	0.20	0.59	0.27	0.024	0.016	1.80	0.52	0.24	—	Al 0.084	Diesburg et al.	[32]
—	0.17	0.82	0.27	0.023	0.016	0.84	0.40	0.54	—	Al 0.066	Diesburg et al.	[32]
4817	0.17	0.59	0.25	0.025	0.016	3.50	—	0.24	—	Al 0.087	Diesburg et al.	[32]
—	0.17	0.87	0.28	0.023	0.017	1.34	0.58	0.75	—	Al 0.074	Diesburg et al.	[32]
8800	0.2	0.8	0.28	0.020	0.018	0.5	0.47	0.34	—	Al 0.08	Diesburg et al.	[32]
30KhN3A	0.29	0.51	—	—	—	3.02	0.85	—	—	—	Molchanov and Klimov	[33]
30KhN2MFA	0.34	0.50	—	—	—	2.09	0.83	0.27	—	V 0.14	Molchanov and Klimov	[33]
25Kh2N4VA	0.24	0.41	—	—	—	4.30	1.51	0.06	—	W 0.98	Molchanov and Klimov	[33]
—	0.36	0.82	0.20	—	—	—	1.10	0.16	—	—	Akizono et al.	[34]
SCM21	0.16	0.70	0.25	—	—	—	1.10	0.25	—	—	Furukawa et al.	[25]
SNCM25	0.15	0.45	0.25	—	—	4.35	0.90	0.22	—	—	Furukawa et al.	[25]
15C	0.15	0.76	0.20	0.017	0.018	—	1.02	0.16	—	—	Horimoto et al.	[35]
20C	0.21	0.83	0.23	0.016	0.014	—	1.08	0.16	—	—	Horimoto et al.	[35]
25C	0.25	0.73	0.19	0.018	0.010	—	0.90	0.18	—	—	Horimoto et al.	[35]
20CM	0.21	0.87	0.08	0.025	0.019	—	1.07	0.38	—	—	Horimoto et al.	[35]
80C	0.78	0.82	0.19	0.014	0.012	—	0.88	0.17	—	—	Horimoto et al.	[35]
40KhNMS	0.42	0.59	0.27	0.019	0.017	1.05	0.8	0.23	—	—	Kozyrev et al.	[36]
12KhN3A	0.11	0.54	0.023	0.012	0.018	2.75	0.85	—	—	—	Kozyrev et al.	[36]
40N10	0.41	0.29	0.09	0.015	0.006	10.4	0.22	—	—	Al 0.04	L'vov et al.	[37]
40N10	0.37	0.17	0.04	0.005	0.005	10.6	0.25	—	—	Al 0.05	L'vov et al.	[37]
40N14	0.39	0.32	0.10	0.010	0.005	14.0	—	—	—	Al 0.05	L'vov et al.	[37]
40N14	0.38	0.19	0.06	0.004	0.003	13.9	0.25	—	—	Al 0.07	L'vov et al.	[37]
30KhGS	0.32	1.16	0.99	—	—	—	1.20	—	—	—	Ermakov	[38]

maraging steel by thermal cycling. This produced a dispersed form of the austenite which increased the resistance of the steel to low cycle impact fatigue. This improvement resulted from the transformation of austenite to ferrite at crack tips thereby producing relaxation of stresses. A large effect of retained austenite on impact fatigue strength was also observed by L'vov et al. [37] working with medium carbon high-nickel steels. The γ to α transformation occurred as a result of the impact loading and, contrary to the findings of Pestov in relation to a maraging steel, the retained austenite worsened the low cycle impact fatigue properties but improved the high cycle properties. Increasing the nickel content of the steel from 10% to 14% substantially improved the impact fatigue strength.

Postovalov and Kileeva [46] tried repeated quenching a Cr–Ni structural steel from the intercritical range to create a dual phase structure. This had the effect of worsening the impact fatigue properties. Baohong et al.

Table 3
Studies of the impact fatigue behavior of miscellaneous ferrous materials reported in the literature

Material	Composition	Authors	Ref.
FC20 cast iron	C 3.38, Si 1.72, Mn 0.32	Owadano et al.	[39]
FC25 cast iron	C 3.26, Si 1.64, Mn 0.32	Owadano et al.	[39]
FCD20 cast iron	C 3.80, Si 2.88, Mn 0.18	Owadano et al.	[39]
Austenitic steel	C 0.54, Si 0.75, Mn 1800, P 0.035, S 0.003, Ni 0.06, Cr 4.84	Nakayama et al.	[40]
Med. Cr. cast semi-steel	C 1.86, Si 0.56, Mn 0.84, Cr 6.12, P 0.031, S 0.028	Change et al.	[41]
Med. Cr. cast semi-steel	Same + 0.21 rare earths	Change et al.	[41]
Austenitic stainless steel	Nominal 18Cr, 9Ni	Yang et al.	[16]
Die steel (bainite + martensite)	C 0.67, W 1.95, Cr 4.7, V 1.10, Ti 0.15, Mo 3.20, Si 1.20, Mn < 0.40	Baohong et al.	[42]
Low Cr–Si cast iron	C 3.08, Cr 2.70, Mn 0.39, Si, 0.55, Mo 0.41, Co 0.095, P 0.015, S 0.05	Li et al.	[43]
Low Cr–Si cast iron	C 2.33, Cr 2.56, Mn 0.90, Si 0.70, Mo 0.13, Co 0.30, P 0.05, S 0.056	Li et al.	[43]
Martensitic high Cr cast iron	C 2.85, Cr 14.51, Mn 0.41, Si 0.84, Mo 0.13, Cu 0.48, Ni 0.12, P 0.035, S 0.03	Li et al.	[43]
Maraging steel	C 0.01, Ni 18.2, Co 9.0, Mo 4.8, Ti 0.75, A1 0.09, Si < 0.05, Mn < 0.05, S < 0.007, P < 0.07	Pestov et al.	[44]
Maraging steel	C 0.01, Ni 17.9, Co 8.9, Mo 5.0, Ti 0.69, A1 3.09, Si 0.02, Mn 0.02, S 0.009, P 0.004	Pestov et al.	[44]

[42] created a martensite–bainite dual phase microstructure in a complex die tool and apparently achieved an improvement in impact fatigue properties.

4.2. Crack nucleation and growth

The nucleation of cracks during impact fatigue of iron with just 0.01% carbon has been studied by Zhang et al. [18,47]. They found that cracks nucleated at grain boundaries and that grain boundaries also acted as barriers to crack propagation. Thus, crack nucleation and growth during impact is in these respects similar to crack nucleation and growth in ordinary tensile tests. Nucleation and growth occurred more readily in grains which exhibited straight slip than in grains which exhibited cross slip. In steels with retained austenite crack nucleation occurs in austenite between martensite laths [48].

Working with a maraging steel and a medium-alloy steel Pestov et al. [45] found that the crack nucleation time was insensitive to the stress applied in impacts. Nakayama et al. [27] found that the crack growth rate in a 0.1% aluminum-killed steel was greater in impact fatigue than in ordinary fatigue for a given cyclic stress. Yang et al. [16] have studied the evolution of dislocation structures during crack nucleation and growth in a 0.1% carbon steel and an austenitic steel. They observed increasing dislocation density followed by the formation of tangles, the development of cells, and the shrinking of these cells, as the impact fatigue proceeded to fracture. Thus, the evolution of dislocation structures during impact fatigue is much the same as their evolution in tensile deformation.

4.3. Fractography

When a product fails by impact fatigue in service its fracture surfaces often impact each other with the result that fracture markings are destroyed. The fracture surface then has a featureless "burnished" appearance [49]. Cheng et al. [26] studied the fatigue of a plain carbon rail steel subjected to sinusoidal or rectangular pulse (impact) loading. They found that the fracture surfaces of specimens tested with sinusoidal loading exhibited markings reflecting the pearlitic structure of the steel. Specimens tested in impact exhibited a quasi-cleavage fracture surface. In contrast to this Nakayama et al. [27] found that impact fatigue of a 0.1% carbon aluminum-killed steel produced largely inter-granular fracture. In other circumstances fatigue striations have been observed on specimens tested in impact fatigue [48].

4.4. Surface modifications

There has been considerable interest in the effects of surface carburizing on impact fatigue properties. Much of this interest stems from the problem of designing gear teeth which will not break in service. Important studies of the impact fatigue behavior of carburized specimens have been published by DePaul [28], Diesburg [50] and Diesburg et al. [32]. Working with six Ni–Cr–Mo low alloy steels DePaul found little effect when he varied core hardness and case depth. Diesburg, Bulla and Fairhorst found that low hardenability steels when carburized showed poor resistance to impact fatigue crack initiation while higher hardenability steels showed higher crack initiation resistance. The best impact fatigue results were obtained with an experimental steel containing 0.87%Mn, 0.58%Cr, 1.84%Ni and 0.75%Mo. Working with five Cr–Mo low alloy steels Horimoto et al. [35] found that increasing core hardness and use depth improved impact fatigue properties. Thus, there seems to be a disagreement between DePaul's work on Ni–Cr–Mo alloys and this work of Horimoto et al. on Cr–Mo alloys. Other surface hardening treatments which have been tried include steel shot blasting [51] and a CrN layer over a nitrided surface [52]. Both methods achieved an improvement in impact fatigue properties.

4.5. Temperature and environment

Several studies of the effects of temperature on the impact fatigue properties of steels have been reported. Yarema and Kharish [15] have studied the impact fatigue properties of a Ni–Cr steel between room temperature and $-120\,^{\circ}C$. They found that the overall endurance of the steel improved as the temperature decreased. The time to initiate a crack increased with decreasing temperature but the time to propagate it decreased. Using a Cr–Mo steel Akizono et al. [34] found that as the temperature was lowered from room temperature to $-150\,^{\circ}C$ intergranular cracking and cleavage became favored over striation formation and crack growth rate accelerated.

Matsumure et al. [23] studied the impact fatigue properties of two plain carbon steels at room temperature and $-30\,^{\circ}C$. They had carbon contents of 0.39% and 0.63%. For both steels they found that at room temperature the impact fatigue life was shorter than that for conventional fatigue and the crack propagation rate was higher. With the lower carbon steel cleavage was observed at $-30\,^{\circ}C$ but not at room temperature. With the higher carbon steel cleavage was observed at both temperatures. The plastic zone depth beneath the fracture surface in impact fatigue specimens was found to be only about one-third of the depth in conventional fatigue specimens.

5. Engineering failures

Although engineering failures must have stimulated much of the published work on impact fatigue, not many of the failures have been described in the literature. Johnson and Keller [49] have described the failure of screens used in a grinder in which blocks of artificial rubber were converted to granules. The screens were made from 8620 low alloy steel heat treated to give it a spheroidized microstructure. One might expect that this relatively soft material would have poor impact fatigue properties, but there appears to be no research demonstrating that.

Johnson [54] has described the failure of a nail hammer. The knurled striking surface of the hammer chipped causing a serious eye injury. A study of the hammer material showed that it was made from a 0.75% carbon steel which locally at the failure site had a high concentration of manganese sulfide precipitate particles. Impact fatigue cracks had propagated from particle to particle.

6. Summary

In this paper, the authors have reviewed enough of the international literature on the impact fatigue properties of irons and steels to create a fairly clear picture of where the field stands. Most of the work so far published has been on irons, plain carbon steels and alloy steels, with the alloy steels being by far the largest group. Many different specimen configurations and types of testing machine have been used with the result that in general the results of these studies cannot be compared one with another. There is an urgent need for the development of international standards for both specimens and testing machines.

In spite of these problems some general features of impact fatigue in irons and steels have emerged. They can to a large extent be understood by considering the implications of the fact that impact fatigue involves strain-rates of the order of $10^3\,s^{-1}$. Typically an impact is over in a few milliseconds. Strain-rates in conventional fatigue testing and in conventional testing are much lower.

Increasing the strain-rate increases the yield stress, ultimate tensile strength and ductile–brittle transition temperature of an iron or ferritic steel. Thus, in general, the impact fatigue strength is higher than the conventional fatigue strength. Because a given temperature is closer to the ductile–brittle transition in impact fatigue, cleavage tends to be favored over a ductile mode of fracture. The ductility being less, the plastic deformation zone behind the fracture surface is smaller.

The nucleation of cracks in impact fatigue is similar to that in other kinds of testing. The cracks nucleate at grain boundaries presumably by the coalescence of dislocations at the tips of dislocation pile-ups or by the attainment of the theoretical fracture stress ahead of the pile-ups. Nucleation of cracks at twin intersections does not seem to have been reported yet, but this will probably happen. As in tensile testing, cracks can be held up at grain boundaries during an impact fatigue test.

Some progress has been made with the study of the effects of surface modifications on impact fatigue. Improved properties have been achieved by hardening surfaces through carburizing, nitriding and bombarding with steel shot. The study of the effects of corrosive environments has barely begun. There is some evidence that there exists an effect which we can call ''impact corrosion fatigue'' which is analogous to corrosion fatigue [31,53].

References

[1] *Report of the Commission Appointed to Enquire into the Application of Iron to Railway Structures*, 2 Vols., London, 1849.

[2] T.E. Stanton, L. Bairstow, The resistance of materials to impact, *Proceedings of the Institute of Mechanical Engineers*, 1908, pp. 889–919.

[3] D.J. McAdam Jr., Endurance properties of steel: their relation to other physical properties and to chemical composition, *Proceedings of ASTM* 23 (2) (1923) 56–105.

[4] G.A. Hankins, H.R. Mills, The resistance of spring steels to repeated impact stresses, *Journal of the Iron and Steel Institute (London)* 131 (1935) 165–180.

[5] A.A. Johnson, D.J. Keller, The impact fatigue properties of pearlitic plain carbon steels, *Fatigue of Engineering Materials and Structures* 4 (3) (1981) 279–285.

[6] D.N. Johnson, A.A. Johnson, The low cycle impact fatigue properties of pearlitic plain carbon steels, *Fatigue and Fracture of Engineering Mateirals and Structures* 8 (3) (1985) 287–294.

[7] K. Kishimoto, T. Wakabayashi, S. Aoki, M. Sakata, Evaluation of dynamic stress intensity factor in impact bending fatigue testing, *Zairyo* 31 (344) (1982) 478–482.

[8] S. Taira, H. Iguchi, K. Tanaka, Development of impact fatigue testing machine and some test results, *Proceedings of the 22nd Japan Congress on Materials Research*, 1978, pp. 181–186.

[9] H. Iguchi, K. Tanaka, S. Taira, Failure mechanisms in impact fatigue of metals, *Fatigue of Engineering Materials and Structures* 2 (1979) 165–176.

[10] A. Chatani, T. Kawada, H. Nakazawa, I. Nakahara, The deformation and strength of mild steel subjected to repeated impact tensile stresses, *Journal of the Society for Materials Sciences Japan* 17 (1968) 408–414.

[11] E.L. Kharish, S. Ya. Yarema, A.B. Kuslitskii, G.D. Stefanov, Influence of impurities and structure on the fatigue life of steel 30KhGSNA, *Materials Science* 10 (1) (1975) 96–97.

[12] S. Taira, H. Iguchi, K. Tanaka, Effect of loading wave shape on deformation and failure in impact tensile fatigue of smooth specimen of carbon steel, *Journal of the Society for Materials Sciences Japan* 27 (301) (1978) 942–947.

[13] T. Uchida, N. Okabe, T. Yano, M. Ishimatu, T. Mori, Prediction of crack initiation and crack propagation life of carbon steel subjected to repeated impact tensile loads, *Zairyo* 29 (320) (1980) 492–498.

[14] N. Okabe, T. Yano, T. Mori, Probabalistic estimation of fatigue strength for structural carbon steels 10 subjected to repeated impact tensile loads, *Zairyo* 30 (328) (1981) 28–33.

[15] S. Ya. Yarema, E.L. Kharish, Crack nucleation and growth periods in 30CrMnSiNiA steel under repeated-impact tensile loads, *Materials Sciences* 5 (1972) 432–434.

[16] P. Yang, Y. Tan, H. Zhou, Impact fatigue behaviors and dislocation structures in low carbon steel and austenitic stainless steel, *Proceedings of the Conference on Strength of Materials*, Japan Institute of Metals, 1994, pp. 497–500.

[17] H. Nakayama, T. Tanaka, Impact fatigue crack growth behaviors of high strength low alloy steel, *International Journal of Fracture* 26 (1984) R19–R24.

[18] M. Zhang, P. Yang, Y. Tan, Y. Liu, S. Gong, An observation of crack initiation and early crack growth under impact fatigue loading, *Materials Science and Engineering A* 271 (1999) 390–394.
[19] A. Yanagisawa, T. Ishigai, M. Kiyama, Impact fatigue test machine for grinding balls, US Patent 4375762, 1983.
[20] W. Li, X.-h. Tu, J.-y. Su, Q.-d. Zhou, Microstructure, impact fatigue resistance and impact wear resistance of wear resistant low Cr–Si cast iron, *Journal of the Iron and Steel Institute International* 8 (2001) 17–20.
[21] F. Han, S. Shen, D. Wang, X. Chen, X. Lu, Study on the structure and properties of a novel minisized high Cr mill balls, *Wear* 253 (5–6) (2002) 640–649.
[22] T. Owadano, K. Nagai, K. Kishitake, Impact fatigue test results for cast irons, *Imono* 53 (5) (1981) 221–226.
[23] T. Matsumure, Y. Inoue, T. Takagi, Impact fatigue fracture of axle steel and tire steel, *Tetsudo Gijitsu Kenkyogo, Quarterly Report* 24 (2) (1983) 94–95.
[24] K. Akizono, R. Murakami, On the impact fatigue crack growth behavior in butt welded joint of mild steel (Report 1), *Yosetsu Gakkaishi Society* 48 (11) (1979) 971–979.
[25] T. Furukawa, S. Konuma, H. Sakaniwa, Effects of chemical composition and heat treatment on mechanical properties of carburized steels, *Journal of the Iron and Steel Institute of Japan* 65 (8) (1979) 1204–1212.
[26] Y. Cheng, D. Chen, F. Nogata, Fatigue behaviour of a rail steel under low and high loading rates, *Fatigue and Fracture of Engineering Materials and Structures* 17 (1) (1994) 113–118.
[27] H. Nakayama, Y. Kanayama, T. Tanaka, Study on crack growth behaviour in impact fatigue (Part 1, Impact fatigue crack growth characteristics of 0.1% C aluminum killed steel), *Bulletin of the Japanese Society of Mechanical Engineers* 26 (219) (1983) 1453–1460.
[28] R.A. DePaul, *High Cycle and Impact Fatigue Behavior of Some Carburized Gear Steels*, International Nickel Co., Suffern, NY, 1971 4pp.
[29] B.S. Shul'ginov, V.A. Matveyev, Impact fatigue of low-alloy steels and their welded joints, *International Journal of Fatigue* 19 (8–9) (1997) 621–627.
[30] G.V. Kozyrev, G.V. Toporov, Effect of retained austenite on the impact fatigue strength of steel, *Metallovedenie i Termicheskaya Obrabotka Metallov* (12) (1973) 45–48.
[31] D.-f. Yang, Z.-y. Zhao, Corrosion impact fatigue behavior of AF1410 steel and 300M steel, *Journal of Materials Engineering (Beijing)* (Part 1) (2003) 3–5, 7.
[32] D.E. Diesburg, W. Bella, W. Fairhurst, Resistance of carburized steels to crack initiation in impact fatigue, *Proceedings of the International Heat Treating Conference*, International Federation for the Heat Treatment of Materials, Barcelona, Spain, 1978.
[33] L.N. Molchanov, K.V. Klimov, Heat treatment and impact-fatigue strength of alloy steels, *Metal Science and Heat Treatment* 21 (5–6) (1979) 470–472.
[34] K. Akizono, R.-i. Murakami, S. Takenouchi, Impact fatigue crack growth behavior at low temperatures, *Zairyo* 29 (321) (1980) 585–591.
[35] M. Horimoto, H. Matsimoto, T. Makino, N. Murai, K. Onita, Y. Arimi, S. Fujikawa, T. Nishino, Effect of core hardness and case depth on low-cycle-impact-fatigue property in carburized steel, *Journal of the Society for Materials Science Japan* 52 (11) (2003) 1318–1324.
[36] G.V. Kozyrev, G.V. Toporov, K.K. Karandashov, V.P. Pershin, L.A. Kolodeznyi, Evaluating the resistance of surface-hardened steels to impact-fatigue fracture, *Strength of Materials* 13 (6) (1981) 700–703.
[37] Yu.B. L'vov, M.D. Perkas, A.Ya. Maloletnev, R.D. Zaitseva, Impact-fatigue strength of medium carbon high-nickel steel, *Metal Science and Heat Treatment* 20 (5) (1978) 353–356.
[38] E. Ermakov, Impact fatigue of chromium–manganese–silicon steel KhGs, *Metal Science and Heat Treatment* 1 (2) (1959) 39–42.
[39] T. Owadano, K. Nagai, K. Kishitake, On the results of impact fatigue test of cast iron, *Imono* 53 (5) (1981) 221–226.
[40] H. Nakayama, Y. Kanayama, Y. Fukui, Y. Kitamura, Fatigue strength of 18Mn–5Cr non-magnetic steel, *Zairyo* 30 (329) (1981) 119–122.
[41] L.-m. Chang, J.-h. Liu, S.-x. Yu, Y. Chen, Effect of rare earth elements and heat treatment on impact fatigue property of medium chromium cast semi-steel, *Jin shu re chu li (Heat Treatment of Metals)* 27 (1) (2002) 25–26.
[42] T. Baohong, W. Lei, Z. Shian, L. Quan, L. Hongzhao, Y. Ke, Study on the impact fatigue of 12 martensite–bainite dual phase structure in 65Cr5Mo3W2VSiTi steel, *Heat Treatment of Metals (China)* 1 (1995) 13–15.
[43] W. Li, X.-h. Tu, J.-i. Su, Q.-d. Zhou, Microstructure impact fatigue resistance and impact wear resistant low Cr–Si cast iron, *Journal of Iron and Steel Research International* 8 (2001) 17–20.
[44] I.V. Pestov, A.Ya. Maloletnev, M.D. Perkas, A.F. Edneral, Low-cycle impact fatigue strength of steel N18K9MST with a biphase $\alpha+\gamma$ structure, *Metal Science and Heat Treatment* 23 (4) (1981) 261–265.
[45] I.V. Pestov, V.A. Ostapenko, M.D. Perkas, A.Ya. Maloletnev, N.A. Kretov, Kinetics of crack growth in maraging and medium-alloy steels during low-cycle impact fatigue tests, *Metal Science and Heat Treatment* 19 (7) (1977) 512–517.
[46] V. Postovalov, A.I. Kileeva, Fatigue properties of a structural steel quenched from an intercritical temperature range, *Metal Science and Heat Treatment* 23 (7–8) (1981) 501–502.
[47] M. Zhang, P. Yang, Y. Tan, Micromechanisms of fatigue crack nucleation and short crack growth in a low carbon steel under low cycle impact fatigue loading, *International Journal of Fatigue* 21 (1999) 823–830.
[48] J. Yu, P.K. Liaw, M. Huang, The impact fatigue fracture of metallic materials, *Journal of Materials* 5 (4) (1999) 15–18.
[49] A.A. Johnson, D.J. Keller, Screen failures in a grinder used in the manufacture of artificial rubber, *Proceedings of the International Symposium for Testing and Failure Analysis*, San Jose, CA, 1982, pp. 226–230.
[50] D.E. Diesburg, High-cycle and impact fatigue behavior of carburized steels, Society for Automotive Engineers, Technical Paper 780771, 1978, 10pp.

[51] V.A. Pyshkin, V.A. Yakovlev, V.Ya. Kuznetsov, S.A. Abramenko, Increasing the impact fatigue strength of ring valve plates, *Chemical and Petroleum Engineering* 12 (12) (1976) 1114–1115.
[52] J.D. Kamminga, First results on duplex coatings without intermediate mechanical treatment, *Surface and Coatings Technology* 174–175 (2003) 671–676.
[53] A.A. Johnson, Impact-fatigue—an emerging field of study, *Proceedings of the International Conference on Fatigue 2003*, Engineering Integrity Society, Cambridge, 2003, pp. 257–266.
[54] A.A. Johnson, Concurrent product and process design to avoid impact fatigue failures, *Proceedings of the Second International Conference on Engineering Design and Automation*, Maui, Hawaii, 1998, MSS 327 (CD-ROM).