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(54) **High-strength air cooled steel alloy, manufacturing method and hot worked product**

(57) The invention relates to a steel alloy, which in hot-worked condition has a ferritic-pearlitic microstructure and austenite grain size coarser than ASTM 10 (coarser than 10 μm), and which has a chemical composition of:

C	0,15...0,6 percent by weight
Si	1,25...2,0 percent by weight
Mn	0,5...1,6 percent by weight
S	0...0,2 percent by weight
Cr	0 ...1,5 percent by weight
Mo	0,02...0,1 percent by weight
Al	0 ...0,1 1 percent by weight
V	0 ...0,2 percent by weight
N	0 ...0,04 percent by weight
Nb	0 ...0,1 percent by weight
Ti	0 ...0,05 percent by weight.

The invention relates additionally to methods for manufacturing ferritic-pearlitic hot forged products and hot-rolled steel bars having a high yield strength, high fatigue strength and good machinability.

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Description

[0001] The invention relates to steel, and to a forged product manufactured therewith and characterized by a totally ferritic-pearlitic microstructure without bainite and, accordingly, by a high strength, a particularly high fatigue strength, and good machinability

[0002] The use of air cooled microalloyed steels in hot-forged products is economically sensible as the pieces require no hardening and tempering. However, a problem with these microsteels is a modest strength, especially a low yield strength, when compared to tempered alloy steels. For example, in EN 10267:1998 standard, the highest strength microalloyed forging steel is 46MnVS6, having a minimum yield limit of 580 MPa. In practice, however, the most popular grade is 38MnVS6, having an $R_e = 520 \text{ N/mm}^2$.

[0003] The strength of air cooled microalloyed steels can be improved by increased alloying, for example by adding manganese and/or chromium. However, increased alloying creates a problem as a result of the formation of bainite in the microstructure of steels. An objective in such steels is to obtain a totally ferritic-pearlitic microstructure capable of providing the desired properties. Even small amounts of bainite in the microstructure undermine mechanical properties by decreasing yield strength and toughness, especially elongation and reduction of area in tensile test, as well as by degrading machinability. An element particularly active with regard to the development of bainite is molybdenum, which in such steels must be considered an impurity and the concentration of which must be often limited to as low as not more than 0,03...0,04 wt-%. Occasionally, in the microstructure is formed not only bainite but also untempered martensite, the effect of which on the above properties is even more deteriorating than that of bainite.

[0004] Since, in addition to molybdenum, there are also other effective alloying elements, the tendency to bainite formation can be practically demonstrated by the following summation in wt-%:

$$X = 2\text{Mn} + 5\text{Mo} + \text{Cr} + \text{Ni},$$

wherein Mn, Mo, Cr and Ni represent concentrations of these particular alloying elements in weight percentage. According to prior experience, if $X > 3,1...3,3$, bainite develops in air cooling at thin (20 mm) diameters.

[0005] One way of upgrading the strength of air cooled forging steels is to subject them to such intensive alloying that their microstructure becomes completely or at least substantially bainitic. An example of such steels is described in the publication US 5820706. Instead of direct, simple air cooling, a problem in this technique is maintaining the temperature range of bainite formation, which hampers the forging process and brings forth one more source of process error. Moreover, there are problems regarding the machinability of such steels, especially because from retained austenite they can also easily develop small amounts of hard untempered martensite in addition to bainite. Generally, especially with forged products of considerable thickness, it is also necessary to increase the alloy content of such steels, thus resulting in high manufacturing costs.

[0006] Another example of bainitic steels is a steel as set forth in the published EP application 00850178.5, which is cooled in air. A problem in this case is also a poor and uneven machinability and an increase of alloy content. Since attaining a totally bainitic structure by air cooling without retaining a constant temperature is difficult in practice, in the microstructure usually formed untempered martensite as well. In order to attain even a moderate toughness and machinability, it is generally necessary that the pieces be also annealed for softening hard martensite regions, which increases costs even more.

[0007] It is known that a fatigue strength higher than conventional can be achieved in microalloyed steels rich in silicon. A steel like this is disclosed in the publication EP 0572246B1. A problem here is a low yield strength which is also typical of microalloyed steels in general.

[0008] The bainite formation in conventional microalloyed steels rich in manganese is sometimes discouraged by decelerating their post-forging cooling by providing for example a tunnel around the cooling line. However, this represents an extra cost and, at the same time, another source of error in the manufacturing process.

[0009] It is obvious in light of the above that, by finding a steel alloying based way of precluding bainite formation, the strength of microalloyed steels can be enhanced without disrupting the properties. Thus, it is economically feasible to achieve simultaneously high yield strength, good toughness and good machinability.

[0010] In part making usually the greatest individual cost is machining. It is well known that a fine grain size deteriorates machinability of steel. Therefore, a prior austenite grain size coarser than 10 ASTM (greater than about 10 μm in grain diameter) in the material of workpiece is advantageous. Therefore, an object of the invention is to provide a steel alloy having improved machinability combined with high yield stress and toughness.

[0011] In order to accomplish the objectives of the invention, a steel of the invention is characterized by what is set forth in the characterizing clause of claim 1.

[0012] With respect to the inventive steel, the simultaneous use of silicon alloying and molybdenum alloying results economically a high-strength steel, having a structure which is purely ferritic-pearlitic with neither bainite nor martensite nor drawbacks inflicted thereby.

[0013] Further, the use of chromium concentrations within the range of appr. 0,5 wt-% to appr. 1,5 wt-% enables an improvement in the nitriding properties of steel. The chromium concentration is preferably within the range of appr. 0,5

wt-% to appr. 0,8 wt-%.

[0014] Being a major nitride producer, the chromium alloying causes development of chromium nitrides in the ferritic diffusion layer of a nitrided surface, thus increasing the layer's hardness. For example, 1 wt-% of chromium provides a hardness of about 600 HV (K-E. Thelning, Steel and its Heat Treatment, Butterworths 1975 pp. 86-87). This hardness in the diffusion layer is sufficient even for highly demanding mechanical engineering. As nitride producers, titanium and vanadium also provide activities similar to that of chromium, thus enhancing the latter's effect.

[0015] Compared with unalloyed steel or steel with no alloying elements capable of forming nitrides, the diffusion layer in chromium-alloyed steel has a hardness which is several hundred HV degrees higher, which provides a solid base for an extremely hard compound layer present in the outermost surface. Vanadium and titanium alloying enhances this effect. A surface layer nitrided as described is more resistant to a surface pressure without a risk of cracking, which makes it possible to use the steel e.g. for gears and shafts. A hard diffusion layer means usually also a greater consolidated layer thickness for improved fatigue strength. This is favourable, for example in nitrided crankshafts.

[0016] On the other hand, an excessively high chromium concentration reduces the toughness of forged ferritic-pearlitic steel, which is why it is advisable to retain the concentration at less than 1,5 wt-% and in certain cases at less than 1 wt-%.

[0017] The invention relates also to a method of manufacturing ferritic-pearlitic hot forged products having a high yield and fatigue strength, said method being characterized by what is set forth in the characterizing clause of the independent claim 13.

[0018] Still another object of the invention is a forged product, which is characterized by what is set forth in the characterizing clause of the independent claim 16.

[0019] A yet further object of the invention is a method of manufacturing ferritic-pearlitic hot rolled steel bars having a high yield and fatigue strength, said method being characterized by what is set forth in the characterizing clause of the independent claim 19.

[0020] The invention relates also to a hot rolled steel bar, which is characterized by what is set forth in the characterizing clause of the independent claim 21.

[0021] The following table illustrates mechanical properties and microstructures measured for test steel alloys of the invention as well as corresponding properties in standard reference steels.

Table 1. Chemical composition of test steels and reference steels in weight percentage

Steel	C	Si	Mn	P	S	Cr	Ni	Mo	V	Ti	Als	N
Ref. 1	0,37	0,60	1,31	0,008	0,034	0,13	0,09	0,02	0,11	0,025	0,018	0,011
Ref. 2	0,39	0,55	1,44	0,007	0,037	0,22	0,17	0,04	0,09	0,020	0,021	0,016
Test 1	0,35	1,49	1,57	0,017	0,057	0,18	0,11	0,03	0,12	0,023	0,024	0,014
Test 2	0,36	1,26	1,08	0,010	0,059	0,20	0,14	0,03	0,12	0,014	0,016	0,011
Test 3	0,35	1,46	1,39	0,020	0,059	0,26	0,13	0,06	0,13	0,004	0,007	0,014
Test 4	0,36	1,43	1,33	0,017	0,056	0,27	0,11	0,06	0,16	0,010	0,009	0,021
Test 5	0,36	1,47	1,34	0,017	0,055	0,27	0,11	0,06	0,22	0,010	0,010	0,028

Table 2. Mechanical properties and microstructure in test steels and reference steels. Bar diameter 20 mm. Heat treatment 1200 C air cooling. Legends: Re = yield strength [MPa]; AS = elongation [%]; Z = reduction of area [%]; KCU2 = notch impact strength with 2 mm U-notch bar [J/cm²]; X = sum value representing bainite formation [%], microstructures: F = ferrite, P = pearlite, B = bainite

Steel	Re	A5	Z	KCU2	X	Microstructure	Austenite grain size
Ref. 1	580	16	50	72	2,94	F + P	
Ref. 2	682	8	10	12	3,47	F + P + B	
Test 1	717	15	45	50	3,58	F + P	ASTM 6 (50 μm)
Test 2	651	15	42	39	2,65	F + P	ASTM 4 (100 μm)
Test 3	658	10	20	38	3,47	F + P	
Test 4	735	14	30	40	3,34	F + P	
Test 5	820	13	27	19	3,36	F + P	

Table 3. Mechanical properties and microstructure in test steels and reference steels. Bar diameter 60 mm. Heat treatment 1200 C air cooling. Legends: Re = yield strength [MPa]; AS = elongation [%]; Z = reduction of area [%]; KCU2 = notch impact strength with 2 mm U-notch bar [J/cm2]; X = sum value representing bainite formation [%], microstructures: F = ferrite, P = pearlite, B = bainite

Steel	Re	A5	Z	KCU2	Microstructure	Austenite grain size
Ref. 1	555	18	48	46	F + P	
Ref. 2	591	14	34	12	F + P	
Test 1	647	15	42	19	F + P	ASTM 4 (100 μ m)
Test 2	598	15	42		F + P	ASTM 4 (100 μ m)
Test 3	665	16	38	27	F + P	
Test 4	695	13	34	20	F + P	
Test 5	744	13	33	15	F + P	

[0022] As indicated by the tables, there is no bainite present in test alloys regardless of high alloying rate and molybdenum concentrations. In test alloys, the sum value representing bainite formation is as high as 3,58 without the presence of bainite.

[0023] In reference alloy 2 of the prior art, as expected, bainite is present at the rate of X = 3,47 wt-%. It is further noted that, as a result of bainite, the elongation, reduction of area and impact ductility of said reference alloy are lower than those of the inventive steels. Because of the absence of bainite it is also clear that the inventive steel is better than the reference steels in terms of machinability.

[0024] Raising the carbon concentration to higher than 0,4 wt-% increases strength, but the effect on tensile strength is lesser than on yield strength. On the other hand, at a lower carbon concentration, e.g. 0,15...0,25 wt-%, it is possible to establish a higher yield ratio, which is beneficial in some cases.

[0025] By virtue of silicon alloying, the inventive steel has a fatigue strength which is better than that of standard quenched and tempered and micro-alloy steels, as disclosed in the publication EP 0572246B1.

[0026] In a steel of this invention, the silicon alloying particularly reduces the tendency to bainite formation as evident by comparing a prior known reference alloy (Ref. 2) with test alloys 2...5 of the invention (Tables 1...3), the sum expression thereof giving the value X of higher than 3,3 wt-%. Table 2 also shows how the yield strength, elongation, reduction of area and impact strength of a bainite containing reference alloy (Ref. 2) are distinctly weaker than those of test alloys containing more silicon.

[0027] Manganese and chromium increase strength, but add to the risk of bainite formation at high concentrations.

[0028] An alloying element with a particularly powerful strengthening effect and at the same time promoting bainite formation is molybdenum. In a steel of the invention, molybdenum alloying, together with silicon alloying, has been utilized for increasing strength without drawbacks resulting from bainite. At small dimensions (20 mm), the inventive steel tolerates 0,06 wt-% of molybdenum with no problems, but at large dimensions the cooling rate is slower and higher molybdenum concentrations (e.g. 0,1...0,2 wt-%) are possible without a risk of bainite.

[0029] Vanadium is an effective precipitation hardener. Provided that hot working temperatures are not overly high, vanadium is also functional as a grain-size growth inhibitor. At rather high concentrations, higher than 0,3 wt-%, the use of vanadium is uneconomical and, in addition, toughness is reduced by vanadium. For these reasons it is in some cases advisable to omit vanadium completely.

[0030] Nitrogen is an effective hardener, either as such or together with vanadium. On the other hand, high concentrations, those higher than 0,03...0,04 wt-%, may nevertheless degrade the surface quality of a hot-rolled bar.

[0031] Niobium functions as a precipitation hardener the same way as vanadium.

[0032] Titanium nitrides are capable of withstanding, without dissolving, extremely high temperatures, even higher than 1200 C, which is why a minor addition of titanium is preferred especially in hot forging to inhibit an excessive growth of grain size and to improve toughness. Oversized additions of titanium, however, result in a structure developing large primary TiN particles, which precipitate as early as during solidification and which are ineffective in terms of grain growth and which, by functioning as a crack initiator, undermine toughness and fatigue strength. Moreover, they deteriorate machinability especially at higher cutting speeds. For the maximum machinability Ti should be kept lower than 0,008 wt-%.

[0033] Strength can be enhanced in hot forging by accelerating the cooling rate of the forged product in flowing air, in water-air mist or in some other flowing gas. The inventive steel is highly suitable for such a process by virtue of its minor tendency to bainite formation.

[0034] The range of application for steels of the invention covers hot-forged products, for example parts of automotive

engines, such as crankshafts, connecting rods and pistons.

[0035] In addition, such steels are especially applicable for parts of a vehicular chassis, such as suspension arms, steering arms, front axle beams, etc.

[0036] Chromium-alloyed steel, in particular, is highly applicable for nitrided components, such as crankshafts, gear wheels and pinions.

[0037] In addition, steels of the invention can be used directly in hot rolled condition without forging or heat treatment. Thus, such steels can replace steel bars heat-treated by hardening and tempering. Intended applications include vehicular parts and machine components, for example drive shafts, steering components, fasteners, etc.

Claims

1. A steel alloy, **characterized in that**, in hot-worked condition, it has a ferritic-pearlitic microstructure, austenite grain size coarser than ASTM 10 (coarser than 10 μm), and that it has a chemical composition of:

C	0,15...0,6	percent by weight
Si	1,25...2,0	percent by weight
Mn	0,5...1,6	percent by weight
S	0 ...0,2	percent by weight
Cr	0 ...1,5	percent by weight
Mo	0,02...0,1	percent by weight
Al	0 ...0,1	percent by weight
V	0 ...0,2	percent by weight
N	0 ...0,04	percent by weight
Nb	0 ...0,1	percent by weight
Ti	0 ...0,05	percent by weight.

2. A steel alloy as set forth in claim 1, **characterized in that** Mo = 0,02...0,04 percent by weight.
3. A steel alloy as set forth in claim 1, **characterized in that** Mo = 0,03...0,04 percent by weight.
4. A steel alloy as set forth in claim 1, **characterized in that** Mo = 0,04...0,10 percent by weight.
5. A steel alloy as set forth in claim 1, **characterized in that** Cr = 0,5...1,0 percent by weight.
6. A steel alloy as set forth in claim 1, **characterized in that** Cr = 0,5...0,8 percent by weight.
7. A steel alloy as set forth in any of claims 1-6, **characterized in that** the lower limit of V concentration is 0,04 percent by weight.
8. A steel alloy as set forth in any of claims 1-7, **characterized in that** the lower limit of N concentration is 0,012 percent by weight.
9. A steel alloy as set forth in any of claims 1-8, **characterized in that** the lower limit of Ti concentration is 0,008 percent by weight.
10. A steel alloy as set forth in any of claims 1-8, **characterized in that** the upper limit of Ti concentration is 0,007 percent by weight.
11. A steel alloy as set forth in any of claims 1-10, **characterized in that** the sum $2\text{Mn} + 5\text{Mo} + \text{Cr} + \text{Ni}$ is more than 3 percent by weight.
12. A steel alloy as set forth in claim 11, **characterized in that** the sum $2\text{Mn} + 5\text{Mo} + \text{Cr} + \text{Ni}$ is more than 3,3 percent by weight.

13. A method for manufacturing ferritic-pearlitic hot forged products having a high yield and fatigue strength, **characterized in that** a billet for the forged product is made of a steel alloy having a chemical composition as follows:

C	0,15...0,6	percent by weight
Si	1,25...2,0	percent by weight
Mn	0,5...1,6	percent by weight
S	0 ...0,2	percent by weight
Cr	0 ...1,5	percent by weight
Mo	0,02...0,1	percent by weight
Al	0 ...0,1	percent by weight
V	0 ...0,2	percent by weight
N	0 ...0,04	percent by weight
Nb	0 ...0,1	percent by weight
Ti	0 ...0,05	percent by weight,

and having austenite grain size coarser than ASTM 10 (coarser than 10 μm), and that the method comprises heating the billet to a temperature higher than 800°C and the hot-worked forged product is cooled immediately in a standing or flowing gaseous medium.

14. A method as set forth in claim 13 for manufacturing ferritic-pearlitic hot forged products having a high yield and fatigue strength, **characterized in that** a billet for the forged product is made of a steel alloy having a chemical composition as set forth in any of claims 2-12.

15. A method as set forth in claim 13 or 14, **characterized in that** the method comprises cooling the hot-worked forged product or steel bar immediately in flowing air, in a water-air mixture or in some other flowing gas.

16. A forged product, **characterized in that**, in hot-worked condition, it has a ferritic-pearlitic microstructure as well as a high yield and fatigue strength, and that it has austenite grain size coarser than ASTM 10 (coarser than 10 μm) and a chemical composition of:

C	0,15...0,6	percent by weight
Si	1,25...2,0	percent by weight
Mn	0,5...1,6	percent by weight
S	0 ...0,2	percent by weight
Cr	0 ...1,5	percent by weight
Mo	0,02...0,1	percent by weight
Al	0 ...0,1	percent by weight
V	0 ...0,2	percent by weight
N	0 ...0,04	percent by weight
Nb	0 ...0,1	percent by weight
Ti	0 ...0,05	percent by weight.

17. A forged product as set forth in claim 16, **characterized in that** the steel alloy has a chemical composition as set forth in any of claims 2-9.

18. A forged product as set forth in claim 16, **characterized in that** it has been manufactured by a method as set forth in any of claims 10-12.

19. A method for manufacturing ferritic-pearlitic hot rolled steel bars having a high yield and fatigue strength, **characterized in that** the bar is made of a steel alloy having a chemical composition as follows:

C	0,15...0,6	percent by weight
Si	1,25...2,0	percent by weight

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(continued)

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Mn	0,5...1,6	percent by weight
S	0 ...0,2	percent by weight
Cr	0 ...1,5	percent by weight
Mo	0,02...0,1	percent by weight
Al	0 ...0,1	percent by weight
V	0 ...0,2	percent by weight
N	0 ...0,04	percent by weight
Nb	0 ...0,1	percent by weight
Ti	0 ...0,05	percent by weight,

and having austenite grain size coarser than ASTM 10 (coarser than 10 μm).

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20. A method as set forth in claim 19, **characterized in that** the bar is made of a steel alloy having a chemical composition as set forth in any of claims 2-9.

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21. A hot-rolled steel bar, **characterized in that** it has a ferritic-pearlitic microstructure, austenite grain size coarser than ASTM 10 (coarser than 10 μm) as well as a high yield and fatigue strength, and that it has a chemical composition of:

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C	0,15...0,6	percent by weight
Si	1,25...2,0	percent by weight
Mn	0,5...1,6	percent by weight
S	0 ...0,2	percent by weight
Cr	0 ...1,5	percent by weight
Mo	0,02...0,1	percent by weight
Al	0 ...0,1	percent by weight
V	0 ...0,2	percent by weight
N	0 ...0,04	percent by weight
Nb	0 ...0,1	percent by weight
Ti	0 ...0,05	percent by weight.

22. A hot-rolled steel bar as set forth in claim 21, **characterized in that** the steel alloy has a chemical composition as set forth in any of claims 2-12.

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23. The use of a steel alloy as set forth in any of claims 1-12, a method as set forth in any of claims 13-15 or 19-20, a forged product as set forth in any of claims 16-18 or a bar as set forth in any of claims 21-22 for various vehicular and machine parts either with or without nitriding.

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EUROPEAN SEARCH REPORT

Application Number
EP 05 10 1801

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EPO FORM 1503 03.82 (P04C01)



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EUROPEAN SEARCH REPORT

Application Number
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EPO FORM 1503 03.02 (P04C01)

**ANNEX TO THE EUROPEAN SEARCH REPORT
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