

Silicon Alloyed Ductile Iron with Excellent Ductility and Machinability

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Abstract

Ferritic ductile iron gives considerably more uniform hardness than the ferritic-pearlitic Grade 500-7. Components made from Grade 500-7 often cover the whole of the standard hardness range 170 – 230 HB and are thus more troublesome to machine. To develop a substitute for the standard Grade 500-7, an alloy with a high silicon content was designed. Silicon has a strong stabilising effect on ferrite and at the same time it provides a strong solution hardening effect to the ferrite, which can have a negative impact on ductility especially in combination with other elements like phosphorous.

Machinability of the material has been studied in two ways: 1. Rig tests, where the machinability index was determined 2. Components tested in a real production environment. In the first case, Muhren's model gives a theoretical cost reduction of 10%. To verify this, some components were cast and machined in the ordinary production line. The time reduction (table feeding and cutting speed) was 5 to 20% in production with Si-alloyed material (see **Table 3**). When machining the new material, the noise reduction in the machining hall was considerable, however this improvement was not quantified.

The mechanical properties are better or equal to the conventional Grade 500-7. In Sweden, the material has been given the new standard number SS 0725 with the following properties: $R_m > 500 \text{ MPa}$, $R_{p0.2} > 360 \text{ MPa}$, $A_5 > 10\%$ and $HB = 185-215$. In the new ISO standard, the material will be designated GJS 500-10.

Introduction

Ferritic ductile iron (Grade 400-15 according to ISO 1083 or EN-GJS-400-15 according to EN 1563) gives due to its single-phase matrix products with considerably more uniform hardness than the two-phase (ferritic-pearlitic) Grade 500-7. Components made from Grade 500-7 cover the whole of the standard hardness range 170 - 230 HB. Some of the hardness variation is due to the fact that the pearlite content is affected by the varying cooling rate, which occurs in a component with different dimensions. A particular supplier may in addition have a process-determined range in, for example, chemical composition and inoculation which also leads to variations in pearlite content and hence in hardness, [1,7].

For users of castings the scatter of hardness leads to problems with machining. For example, the machinability of ductile iron with 230 HB has been indicated to be more than halved compared with ductile iron with 170 HB [2-4]. One way of reducing variations in hardness is to produce a material, which is less susceptible to the aforementioned variations. It is well known [2-4] that silicon has a solution-hardening effect on ferrite, i.e. increases its strength, but also lowers the ductility. **Figures 1 and 2** exemplify this.

By producing a single-phase matrix in this way, a narrower range of hardnesses can be expected. This has been demonstrated in previous papers [2-4]. Some questions have however been raised whether or not this is valid in real production situations. To clarify this, production of hub retainers and front axle housings for load dumpers, and front wheel hubs for trucks were studied. In this work machining and ductility aspects are of prime interest. In previous work it has been demonstrated that the mechanical properties of this new material are equal to or better than the conventional Grade 500-7 [2-4,7]. The fatigue properties are also slightly improved, but the most significant aspect is that the scatter in the results is less in the new material compared to the fatigue data found in the conventional Grade 500-7 [7].

Experimental procedures

Material

The test material was cast in the form of hub retainers and front axle housings for load dumpers and front wheel hubs for trucks. **Figures 3 - 5** show the components. The material was used as cast, which is the normal production procedure. The chemical compositions are shown in **Table 1**.

Table 1: Chemical composition of the components made in the silicon alloyed material and in Grade 500-7.

| Component | C | Si | Mn | P | S | Cu | Mg | C _{eq} |
|------------------|------|------|------|----------|----------|------|-------|-----------------|
| Wheel Hub | 3,34 | 3,85 | 0,21 | 0,002 | 0,004 | 0,03 | 0,05 | 4,31 |
| Axle Housing (1) | 3,28 | 3,66 | 0,26 | 0,012 | 0,009 | 0,04 | 0,048 | 4,20 |
| Axle Housing (2) | 3,25 | 3,82 | 0,21 | 0,024 | 0,007 | 0,02 | 0,05 | 4,22 |
| Hub Retainer | 3,25 | 3,74 | 0,21 | 0,024 | 0,007 | 0,02 | 0,05 | 4,20 |
| Grade500-7 | 3,70 | 2,25 | 0,40 | Max 0,05 | Max 0,02 | 0,28 | 0,05 | 4,27 |

$$C_{eq} = C + \frac{Si}{4} + \frac{P}{2}$$

The components were cast in green sand moulds on a Künkel Wagner line. Inoculation at a level of 0.1% was carried out by stream inoculation. An automatic pouring equipment was used.

All tests of the mechanical strength were done on specimens taken from the components. An exemption from this is the material for the ductility tests. These were carried out on specimens taken from cast test plates from various experimental melts.

Machining

The material has been tested in two ways:

- Rig tests, where the machinability index was determined.
- Components tested in real production.

In the first case, this property was tested using a milling operation developed by Volvo Air Corporation [5]. The measure of machinability (or the machinability index) is the wear on the tool. **Table 2** shows the machinability index and Brinell hardness for the different material variants [6]. All materials had a ferritic matrix except for Grade 500-7, which had a ferritic/pearlitic matrix.

Table 2 shows that the machinability index range is relatively narrow for all material variants. The reason for the small variation in the machinability index is due the fact that the test piece has a constant thickness (40 mm). In a way, the relatively low machinability index range does not exactly reflect reality. Normally Grade 500-7 will, for example, vary in hardness due to the variation in material thickness, with the hardness range normally lying between 170 and 230 HB. This range is included in **Figure 6**, which also shows how the machinability index varies with the hardness. The figure shows that the machinability index within the actual hardness range for Grade 500-7 may lie between 40 and 130 units. This causes major problems for machining.

From now on, all assessment will be based on the narrower machinability index range, which will be conservatively calculated for the new material.

Table 2: The machinability index for the materials tested in a rig

| Material | Hardness, HB (5mm/ 750 kp) | Machinability- index | Si (%) | Pearlite (%) |
|--------------|-------------------------------|-------------------------|-----------|-----------------|
| Grade 400-15 | 150 | 200± 5 | 2,35 | 0 |
| Si-alloyed | 195 | 90±5 | 3,74 | 0 |
| Grade 500-7 | 200 | 65±5 | 2,45 | 45 |

The cast components (**Table 1**) were machined in the ordinary production equipment. The wheel hubs for trucks were machined at the Volvo Floby plant, and the hub retainer and the front axle housing were machined at Volvo Construction Equipment in Eskilstuna. For all components the main machining operation was turning and drilling. The results are shown in **Table 3** below.

Results and Discussions

Machinability

The hardness variation in the component is directly related to the machinability index, **Figure 6**, which can be simply converted into machining costs. This is done using the method developed by Volvo Air Corporation [5, 6]. The calculation takes account of the increase in value the component undergone during machining, that is the transformation of a raw casting to a component ready for dispatch. Other aspects that can be accounted for include the types of processing line, shutdown periods, change in machinability index, etc. A calculation was carried out for three components (spring bracket, truck wheel hub and rear axle housing for load dumpers) [2-4,7-8]. The calculation shows that it is possible to reduce the machining cost by 10% by reducing the variation in material hardness. The reduction in hardness variation within a component is about ± 20 HB (2s) in the new silicon alloyed material compared to Grade 500-7, see **Tables 4** and **5**.

The change in the costs, which has been calculated, has been based on the assumption that the entire machinability potential will be exploited. One argument, which has emerged, is that it is not possible to benefit from an improved machinability index with a single process, as in the case of a spring attachment. The machining is unskilled and will take however long it takes. A counter-argument may be that a better machinability index means a higher feed-rate and a smaller number of tool changes on the machine, it means a better production rate and better utilisation of machine capacity than at present. When machining wheel hubs were surface finish and tolerances are important it may be possible that better machinability cannot be fully utilised, as a higher feed-rate may give problems with the surface finish.

It has also been pointed out that in modern production lines tools are not replaced one by one when they are worn out. Tools are replaced in multiples of, for example, 250 parts. This means

that not all tools are worn out, but they are replaced for practical reasons when the line is stopped.

From the argument above it appears that there is considerable potential for reducing costs, even if it is not possible to utilise the whole of the material's potential. The only real way to check the calculation is to make a machinability study using the production equipment. This was done on a limited number of wheel hubs. Two melts with 3,50% and 3,70% Si respectively were prepared, and 50 wheel hubs were cast from each melt. The two melts represent roughly the scatter in chemical composition the foundry has in normal production. An equal number of blanks from the current production, Grade 500-7 were collected to provide a reference. The machining of the normal blanks was done with new tools and with optimised equipment settings. The high silicon material was machined with settings taking the better machinability index into account. Unfortunately, the capacity of the machining line was not great enough. The better machinability index could not be used to the full extent. After comparison with the standard grade, the conclusion reached was that a reduction of at least 6% of the machining cost is possible.

Furthermore, production tests were carried out on 16 front wheel axles and 39 hub retainers for load dumpers. The silicon contents were 3,82 % and 3,66 % respectively (**Table 1**) for the melts produced. The time reduction in **Table 3** refers to table feeding and cutting speed.

Table 3: Results of machining in production with Si-alloyed material (Note Table 1)

| Component | Operation | Time reduction | No of components |
|------------------|---------------------------------------|----------------|------------------|
| Front Wheel axle | Rough and finishing milling, | 10-20 % | 16 |
| Hub retainer | Rough and finishing turning | 5 and 20 % | 39 |
| Wheel hub | Rough and finish turning and drilling | 10 % | 50+50 |

The new silicon alloyed material gave tool wear that was the same or less than for Grade 500-7. The chips were longer than normal, which can give some problems when drilling or threading deep holes. This problem could be overcome by altering the tool and the machining speed.

Hardness measurement

Hardness in the components

From the strength and machinability point of view it is of interest to clarify the actual variation in hardness in a cast component. Two components: one wheel hub and one front axle housing were selected and one section from each component chosen. The same highly experienced person carried out the hardness measurements in both cases. **Figure 7** and **Figure 8** show the positions at which the hardness was measured on the components. Statistical evaluation of the Brinell hardness (5/750) data is shown in **Tables 4** and **5**. Silicon-alloyed material shows a clear reduction in the hardness variation that normally occurs in a hub cast in Grade 500-7. The standard deviation can be reduced from ± 24 to about ± 4 HB by alloying with 3.7-3.8 % Si. The reason for this is the ferritic matrix. The amount of pearlite is reduced to practically zero.

Table 4: Statistical evaluation of the Brinell hardness in the components. Two Wheel Hubs with 3,34 % C and 3,85 % Si, and a Front Wheel Axle with 3,28 % C and 3,66 % Si (Note Table 1)

| | Hub H | Hub L | Wheel Axle |
|------------------------|-------|-------|------------|
| Average | 205 | 207 | 197 |
| Standard deviation, 2s | ± 4,7 | ± 2,7 | ± 1,9 |
| Min | 200 | 202 | 191 |
| Max | 207 | 209 | 198 |
| Max - Min | 7 | 7 | 7 |
| No of HB values | 75 | 73 | 99 |

Table 5: Statistical evaluation of the Brinell hardness in the components. Two Wheel Hubs and a Front Wheel Axle made in Grade 500-7 (Note Table 1)

| | Hub H | Hub L | Wheel Axle |
|------------------------|-------|-------|------------|
| Average | 201 | 215 | 197 |
| Standard deviation, 2s | ± 24 | ± 18 | ± 10 |
| Min | 172 | 197 | 180 |
| Max | 222 | 231 | 207 |
| Max - Min | 50 | 34 | 27 |
| No of HB values | 61 | 59 | 102 |

Hardness in the surface zone

When rough machining is concerned, all hardness gradients in the surface zone are of prime interest. To clarify this the hardness profile was measured in one of the components. Both a micro Vickers indenter (1 kp) and an ordinary Brinell press were used. (HB 5/750). The Brinell indenter was used on the surface after a slight grinding of approximately 0,2 mm. The result indicated 12 HB higher hardness in the surface than 6 mm deeper in the material. For the ordinary Grade 500-7 the opposite was found here the hardness is about 20 HB lower, due to decarburization in the surface.

The Vickers microhardness method shows a clear gradient from the surface and deeper into the material. In **Figure 9**, the results from wheel hubs are shown. When a comparison is made with the Brinell measurements one has to bear in mind that the Brinell test started 0,2 mm under the actual surface due to prior grinding. After a heat treatment at 625°C for 2h the hardness gradient was removed. This proves that the gradient is due to residual stresses.

Ductility

One problem with a species that has a strong solid solution hardening effect like silicon is that the ductility in the material is decreased. Experience from Renault [9] indicates that even 3 % Si in the material, in combination with a moderate addition of phosphorous lowers the ductile to brittle transition.

This experience suggests it is advisable to restrict the phosphorous content for a material with a high content of silicon. In order to clarify this various types of ductility tests were performed.

Impact strength of a material with low phosphorus content

Conventional impact strength testing was carried out at different temperatures on a Charpy-V test bar, figure 10. Each impact value represents an average taken from 3-5 test bars. The transition temperature which can be read from the diagram shows that the transition of Grade 500-7 from ductile to brittle occurs at about + 50°C, whereas in Grade 400-15 with 2.35% Si the transition occurs at about -50°C. The material, which is alloyed with silicon, shows that ferrite, which is solution-hardened by the silicon, has increased brittleness, but still has a transition temperature which is lower than or equal to Grade 500-7.

As mentioned above, the mechanical properties of conventional ductile iron are controlled by means of the composition of the matrix. A higher pearlite content gives greater strength, but at the same time lower elongation and impact strength.

Study of the combined effect of silicon and phosphorus

A series of melts where the silicon and the phosphorus content were varied were produced at two foundries, A and S. The primary results from both tensile tests and impact tests are shown in **Table 6** below [7].

Table 6: Influence of silicon and phosphorus on the ductility and strength.

| Material | Si (%) | P (%) | KV (J) | A ₅ (%) | R _m (MPa) | R _{p0.2} (MPa) |
|----------|--------|-------|--------|--------------------|----------------------|-------------------------|
| S-1 | 2,97 | 0,016 | 13 | 20,0 | 435 | 310 |
| S-2 | 2,98 | 0,045 | 8 | 21,1 | 454 | 329 |
| S-3 | 2,97 | 0,072 | 4 | 19,9 | 471 | 336 |
| S-4 | 3,37 | 0,016 | 6 | 18,7 | 470 | 355 |
| S-5 | 3,37 | 0,043 | 5 | 19,4 | 485 | 370 |
| S-6 | 3,39 | 0,057 | 3 | 19,4 | 502 | 383 |
| A-1 | 3,30 | 0,019 | 5 | 17,9 | 483 | 368 |
| A-2 | 3,23 | 0,044 | 5 | 18,3 | 496 | 38 |
| A-3 | 3,31 | 0,087 | 3 | 16,0 | 523 | 406 |

The impact test in this investigation was done at ambient temperature. In **Table 6**, mean values from at least three specimens are given. The sensitivity of the phosphorus content is high when the content of silicon is low, figure 11.

The other measure of ductility used is elongation to fracture. One clear tendency was found (see **Figure 12**). Despite the scatter the ductility is very good. According to Swedish and other international standards the minimum limit for elongation to fracture is defined as 7% in the standard Grade 500-7. In the silicon-alloyed materials a good margin exists even if the silicon content is as high as 3,7-3,8 %.

The result above indicates that it might be necessary to lower the upper limit of the phosphorus content from max 0,08% for the conventional grade to 0,05%. This is the limit that Renault [9] in France uses for a standard alloy (DBC-450-10) with a maximum allowed Si-content of 3%.

Fracture toughness measurements

Traditionally the fracture toughness parameter K_{IC} has been given as a material constant, which can be used to predict the ability to withstand crack propagation. This is valid for a brittle material. For a more ductile material ($K_{IC} > 20 \text{ MPa m}^{-3/2}$) the conditions for linear fracture mechanics can not be fulfilled without a substantial thickness of the test specimens. Therefore the material has been characterised by a J_{IC} -test, according to ASTM E 813-88. Here the J_{IC} -parameter describes how the ductility of the material interacts with a growing crack that starts from a sharp pre-crack. In this investigation the multiple specimen technique was used. In **Table 7** a mean value of seven specimens is given.

Table 7: Fracture mechanics parameters for the two materials.

| Material | J_{IC} (kN/m) | K_{Id} (Mpa m ^{-3/2}) |
|------------------|-----------------|-----------------------------------|
| Silicon alloyed | 28 | 26 |
| Scatter $\pm 2s$ | 4 | --- |
| EN-GJS-500-7 | 22 | 26 |
| Scatter $\pm 2s$ | 5 | --- |

An alternative to an ordinary J_{IC} -test is an instrumented impact test. Here the pendulum head is equipped with strain gauges and works as a load cell. The method is very fast and inexpensive, but the disadvantage is a greater uncertainty in the output. This test was performed at Daimler-Benz, Germany on an Amsler equipment. The fracture mechanics parameters are calculated with a computer code from Roell-Amsler Testing Machines. The K_{Id} is equivalent to K_{IC} and is determined using ASTM E 399 and ASTM E 992 codes.

From the above the ductility of the silicon alloyed material shows a slightly better toughness than the ordinary standard Grade 500-7. The J_{IC} -value for the Si-alloyed material can, with a statistical certainty be called better. The calculated K_{Id} -value is equal for the two materials, but here a more uncertain test method has been used. If the literature [10] is consulted the scatter for this material parameter for the standard material Grade 500-7 is quite substantial. However a mean value for the Grade 500-7 is given as $25 \text{ Mpa m}^{-3/2}$. This is an indication that the instrumented impact test is quite accurate in this case.

Standard

In **Table 8**, the mechanical properties are specified according to the Swedish standard for silicon alloyed ductile iron. A proposal for the chemical composition is given in **Table 9**.

Table 8: Mechanical properties measured on test pieces machined from separately cast test samples and castings respectively, Swedish standard.

| Grade | | $R_{p0,2}$ MPa min | R_m MPa min | A_5 % min | HB |
|---------|------------|-----------------------|------------------|----------------|---------|
| SS 0725 | Test piece | 360 | 500 | 10 | - |
| SS 0725 | Casting | - | - | - | 185-215 |

Table 9: Chemical composition (proposed aim values)

| Grade | C % | Si % | Mn % max | P % max | S % max | Mg % |
|---------|-----|------|-------------|------------|------------|-----------|
| SS 0725 | 3,3 | 3,75 | 0,3 | 0,05 | 0,02 | 0,02-0,08 |

Conclusion

The theoretical values given previously [2-4] where a cost reduction of 10% in the machining costs could be foreseen has proven to be accurate. A cost saving of 10% is a conservative figure. One area where problems with the material arose was in some drilling operations. Here the long chip formation was a disadvantage. Machining specialists predict that this problem can be overcome with minor adjustments of the tooling and the setting of the machine.

The ductility of the material was tested in various ways, including impact tests down to -50°C conventional tensile tests and with fracture mechanics techniques (J_{1C} , K_{1D}).

| Material | A5 (%) | KV (J) | J_{1C} (kN/m) | K_{1D} (MPa $\text{m}^{-3/2}$) |
|-------------|--------|--------|-----------------|-----------------------------------|
| Si-alloyed | > 16 | 4 | 28 | 26 |
| Grade 500-7 | > 7 | 5 | 22 | 26 |

Ductility of the silicon alloyed material is a minor problem. Even with slightly higher phosphorus content the ductility has a good safety margin compared to the existing value of ductility for Grade 500-7.

Literature references

1. L-E Björkegren; "Influence of chemical composition and structure on the mechanical properties of ductile iron" (in Swedish), Swedish Foundry Association, No 870427 (1987)
2. L-E Björkegren, K. Hamberg, B. Johannesson; "Mechanical Properties and Machinability of Si-Solution-Hardened Ferritic Ductile Iron", AFS Transaction, 96-150, pp 139-145
3. L-E Björkegren, K. Hamberg; "Ductile iron with better machinability compared to conventional grades", Foundryman, Vol 12, 1998, pp386-391.
4. L-E Björkegren, K. Hamberg, B. Johannesson; "Mechanische Eigenschaften und Bearbeitbarkeiten von mit Silicium verfestigten ferritischen Gusseisen mit kugelgraphit", Giesserei-praxis, Nr1 1999, pp 11-17
5. C Muhren; "The impact of machining, new tooling, expensive machine tools and equipment on casting quality requirement", BCIRA International Conference, (1988)
6. Internal report from Volvo Air Corporation, No 6470-71075-01.
7. L-E Björkegren; "Ferritic ductile iron with higher silicon content", (in Swedish), Swedish Foundry Association, No 941028, (1994).

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8. L-E Björkegren , K Hamberg; “Light Ductile Iron Components by Optimization of Material Properties and Design” (in Swedish), Swedish Foundry Association, No. 970930 (1997)
9. J. Legal; Private communication, Renault
10. J Nilsson; “Design Considerations and Materials Data - Ductile Iron” (in Swedish), Swedish Foundry Association, Report No. 971230, (1997).
11. Svensk standard SS14 07 25, “Sferoidal graphite cast iron – SS cast iron 0725, 1998-03-18

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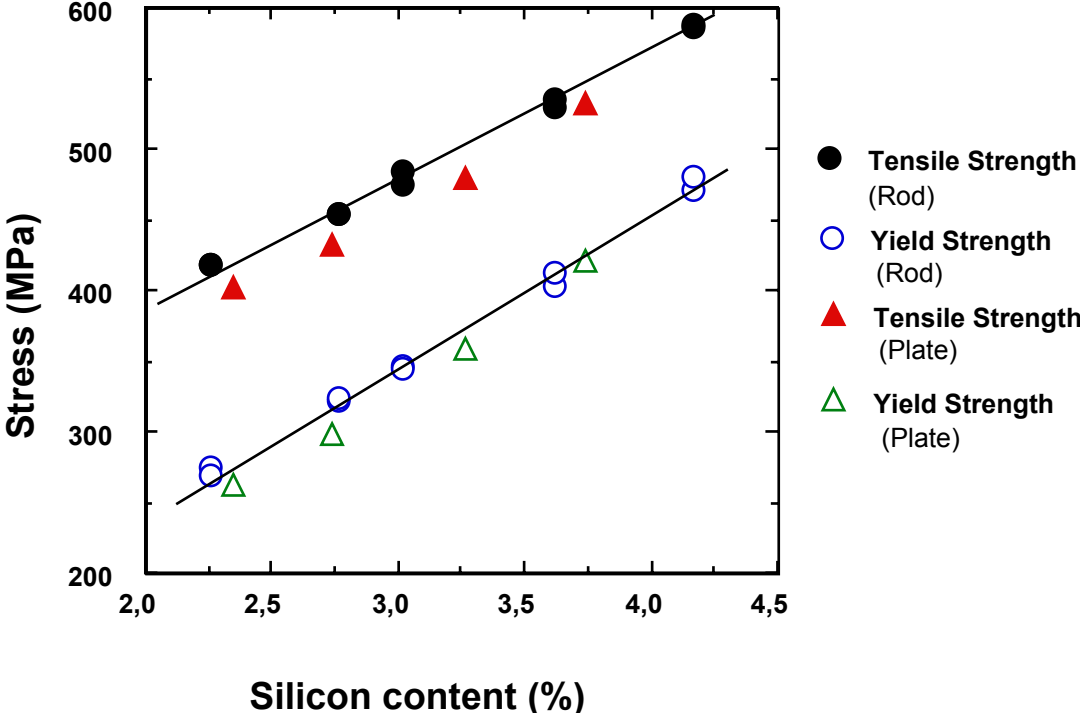


Figure 1: Influence of the silicon content on yield and tensile strength in ferritic ductile iron.

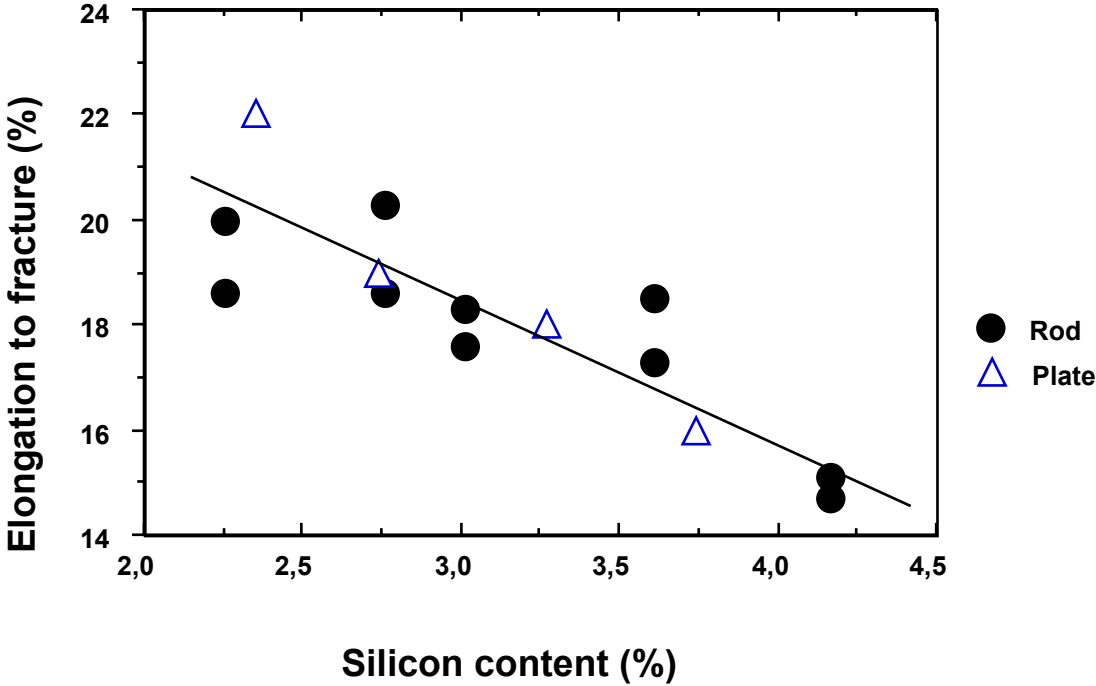


Figure 2: Elongation to fracture as a function of the silicon content in ferritic grades of ductile iron.

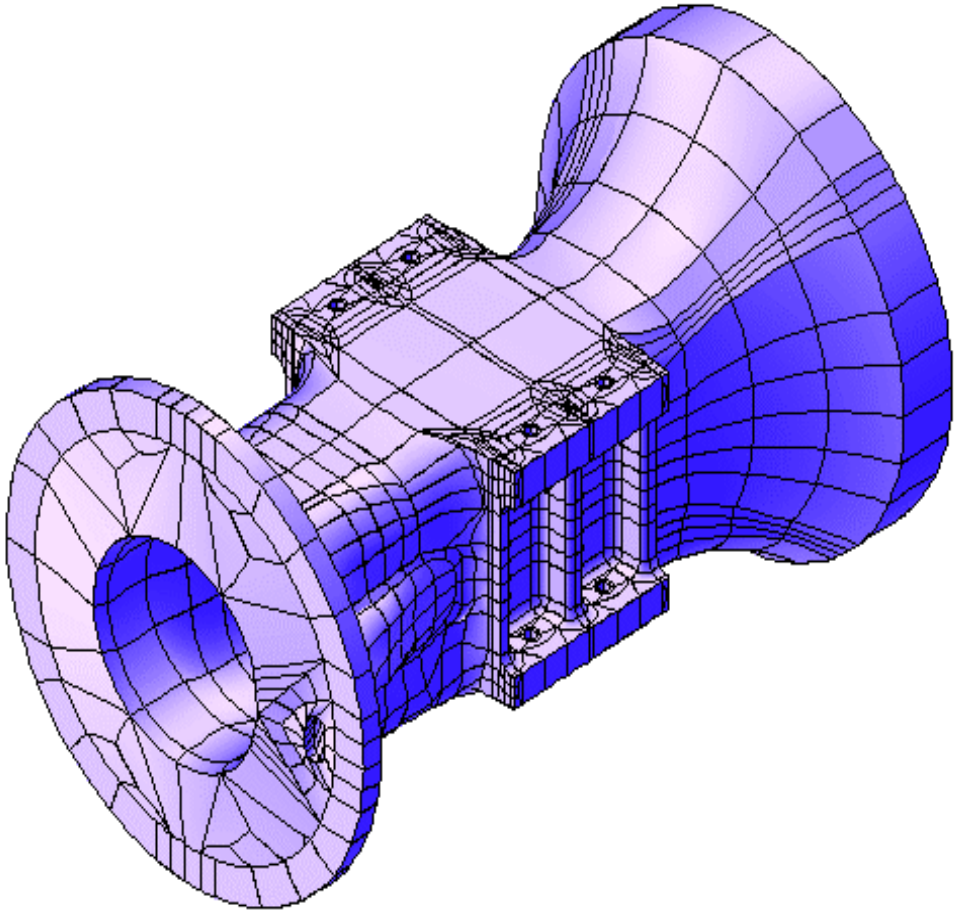


Figure 3: Front wheel axle.

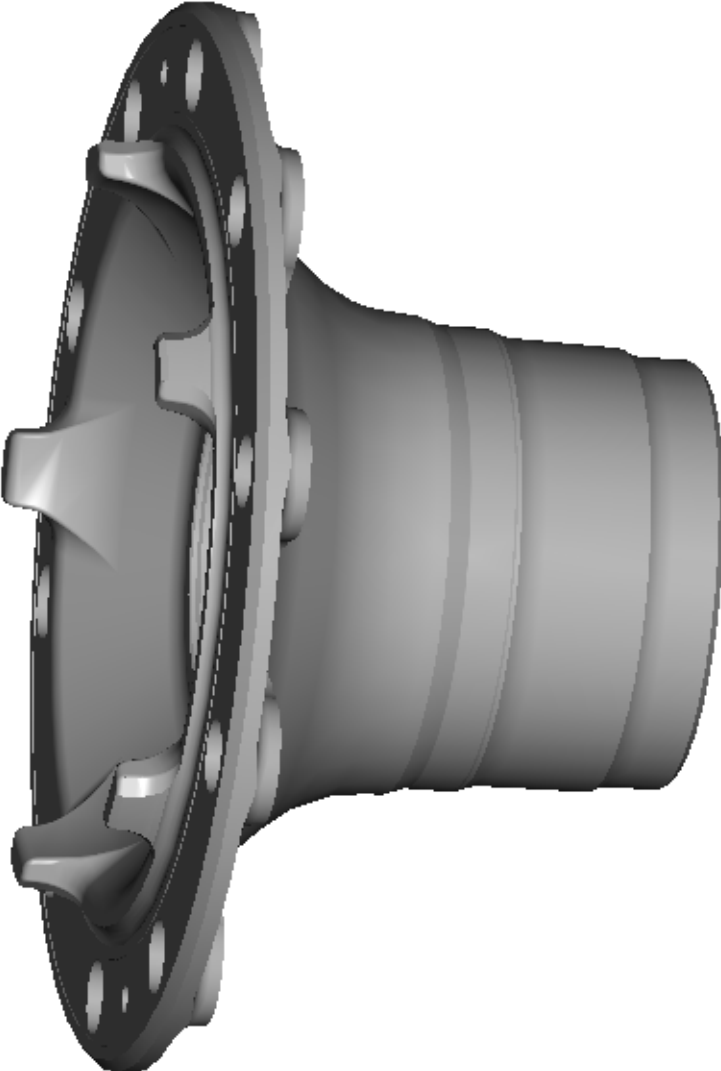


Figure 4: Front wheel hub.



Figure 5: Wheel hub retainer

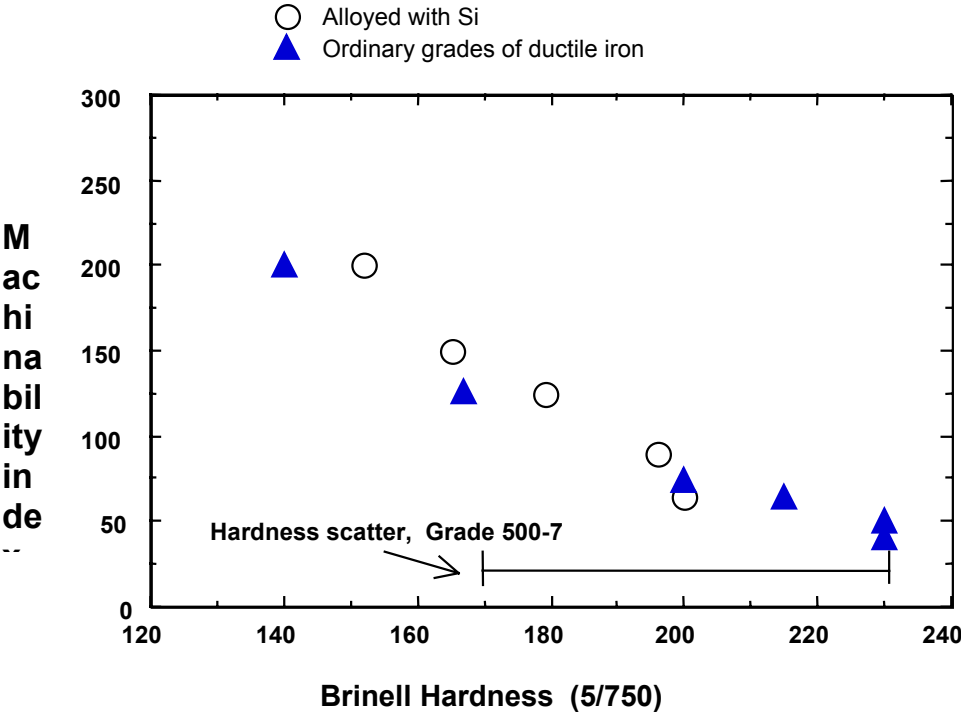


Fig. 6: Machinability index as a function of the hardness in ductile iron.

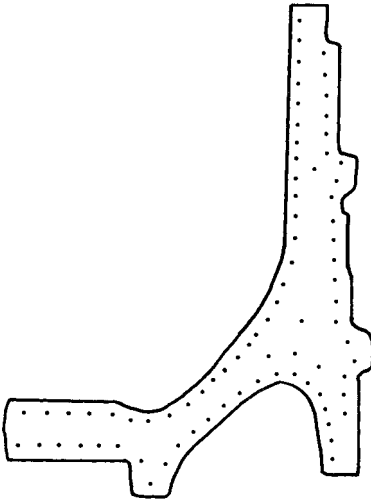


Figure 7: Positions on the wheel hub where the hardness was measured.

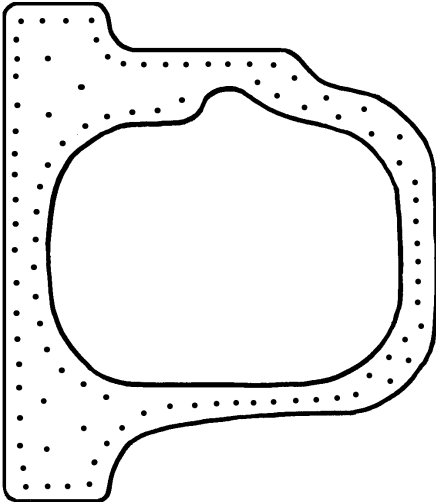


Figure 8: Positions in the front wheel axle where the hardness was measured.

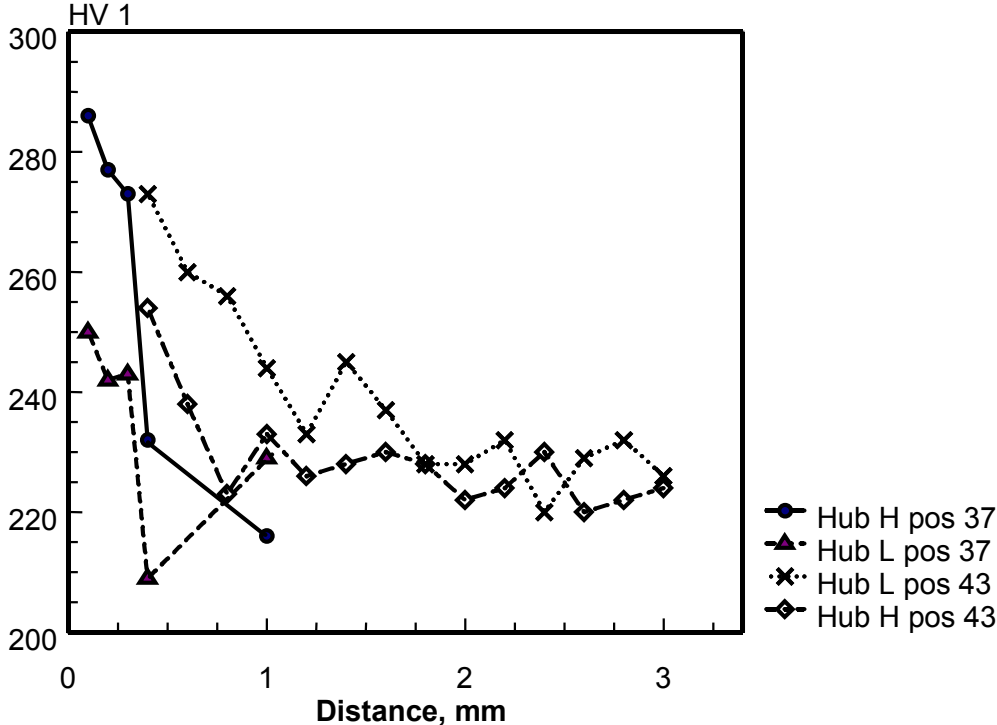


Figure 9: Hardness profile measured at the surface.

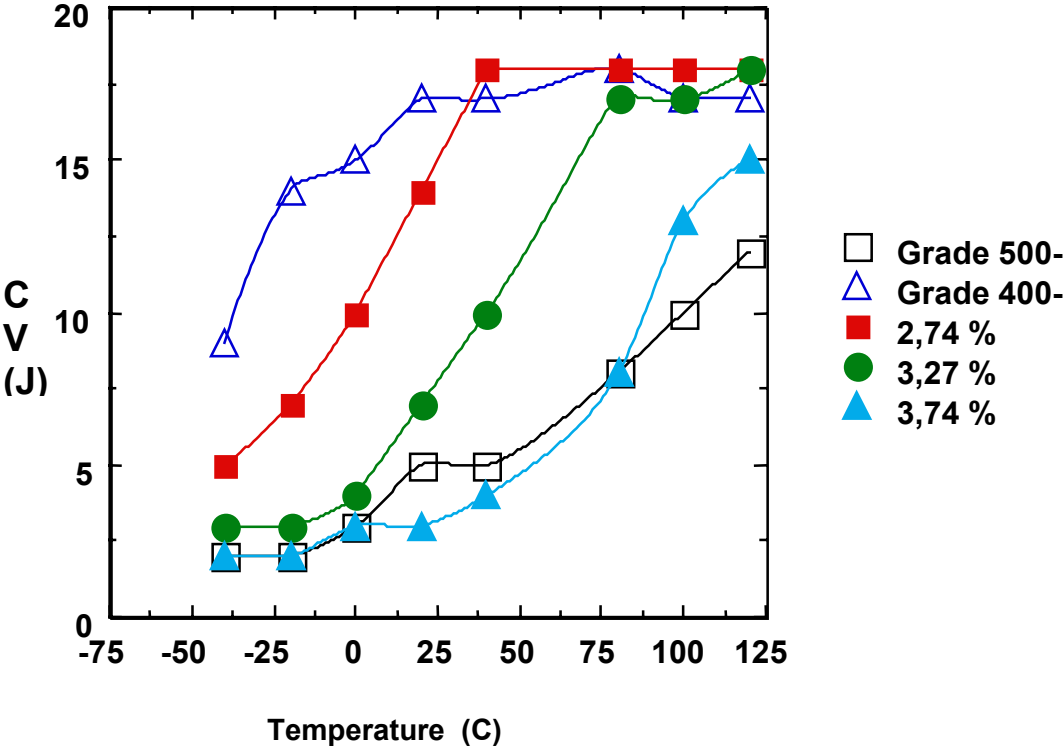


Figure 10: Variation of impact strength with temperature for all tested materials. Test specimens are machined. The material is taken from plate castings.

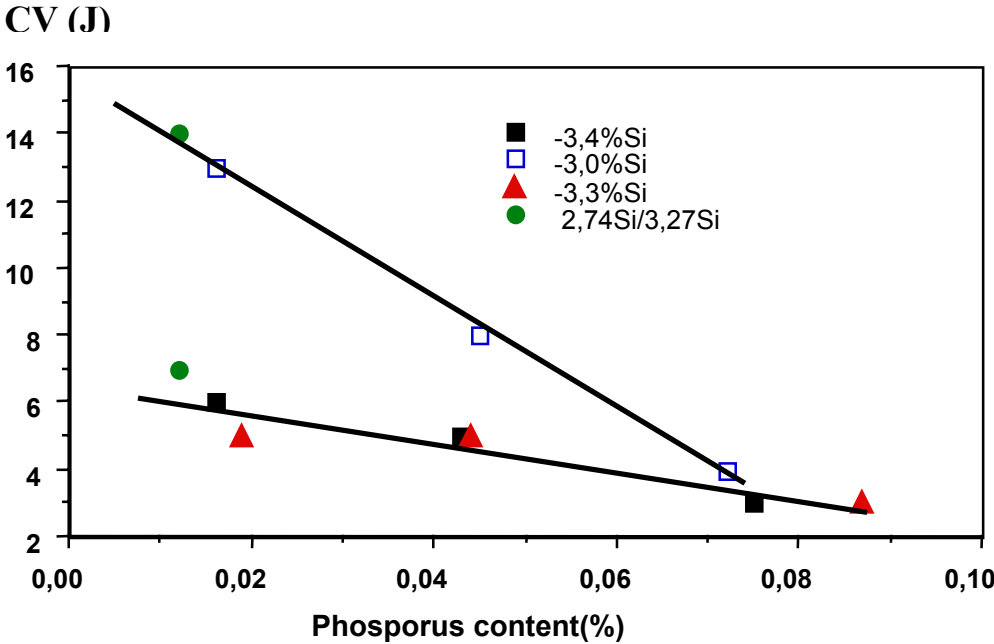


Figure 11: Impact energy as a function of Silicon and Phosphorus content.

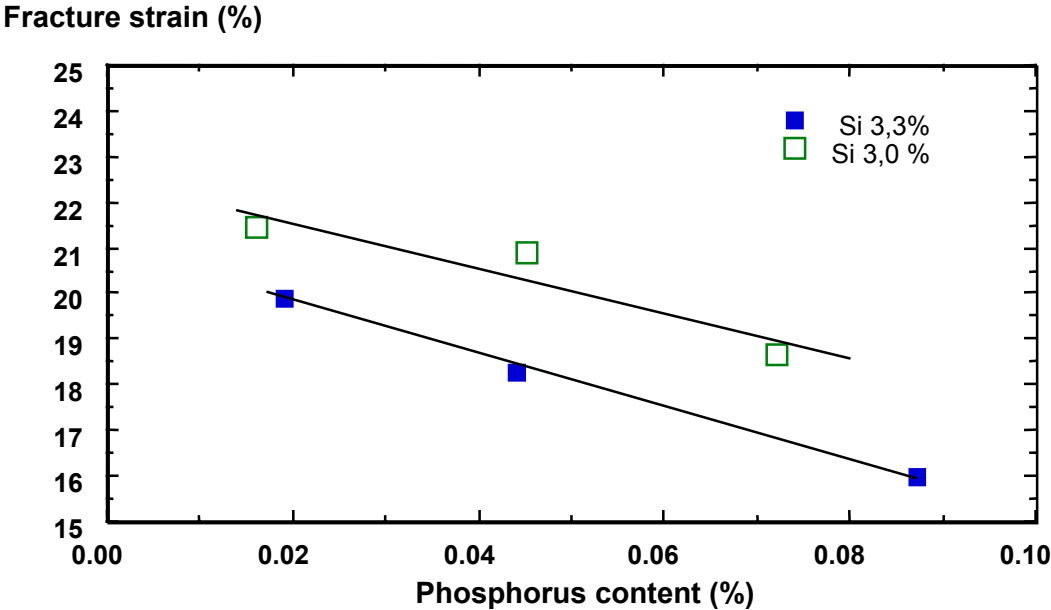


Figure12: Ductility for the material as a function of silicon and phosphorus content.