PROPERTIES AND FRACTURE OF AUTOMOTIVE CONNECTING RODS. A COMPARISON OF STANDARD AND CONTROLLED FORGED LIGHT DIE FORGINGS.

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Automotive connecting rods have been manufactured by standard and controlled die forging. Tensile properties of controlled forged rods are lower, newertheless the fatigue limit and the fatigue fracture morphology are similar to those of standard forged rods. That shows that the controlled forging is a successful process for the manufacture of small machine parts.

1. INTRODUCTION

The standard process of manufacture of light forgings consists of die forging and heat treatment. It is relatively expensive also because three heatings are required for forging, quenching and annealing. The realisation of the idea to carry out these three operations in one heat was strongly promoted by energy saving requirements. Controlled die forging is carried out under a severe control of temperature and the two heat treatment operations are combined in the controlled cooling. The aim is to obtain a microstructure of lamellar pearlite and ferrite, mostly intergranular, and without bainite and probainitic ferrite. Therefore for controlled forging a steel is used with appropriate transformation caracteristics and with carefully balanced elements promoting the bainite transformation.

The controlled forging is at the present successfully applied for the manufacture of light forgings, in medium and heavy machine parts the austenite grain (AS) size and its irregularity present a to serious drawback.

The investigation was carried out in two stages. First in laboratory the transformation, the influence of forging temperature and that of the AG size were investigated and then connecting rods were manufactured by standard and controlled forging. Mechanical properties, microstructure and fracture were investigated.

Inspite of the basic difference in microstructure controlled forged rods show a similar fatigue limit and fracture as standard rods. That shows that controlled forged light forgings could be successfully used for different automotive parts. It is possible that still better properties could be obtained if a steel less propensive to grain growth and with better transformation caracteristics was disponible.

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2. EXPERIMENTAL

Controlled forged connecting rods (rods A) were manufactured from a 0,48 C, 1,2 Mn and 0,3 Cr steel and standard rods from a 0,38 C, 0,78 and 0,58 Cr steel. Both steels were deoxidised with aluminium and in both the content of impurities was kept in the allowed limits. Both types of rods were forged by turns in the same press and tool. For rods A a forging temperature between 1050 and 1250 °C was checked, however for testing only rods forged in a narrower interval of temperature were selected. After forging the rods were controlled cooled to the required microstructure. Rods B were quenched from 860 °C and tempered at 640 °C in a continuous industrial fournace as required by the standard manufacturing process. Tensile and fatigue properties were determined and the microstructure and the fracture morphology investigated. From steel A testing samples were prepared also by one blow forging at temperatures between 1000 and 1300 °C and cooled to the pearlite-ferrite microstructure with the aim to investigate the influence of AG size on properties. This was impossible to establish from the testing of rods because of the irregular AG size ower the section.

3. MICROSTRUCTURE AND PROPERTIES

In die forging a great care must be devoted to the accurateness of the shape of the product. That makes virtually impossible to obtain an uniform AG size ower the section of the piece. For this reason the AG size in controlled forged rods is not uniform. Experience shows that the cause is the deformation at the last blow. This is intended mainly to fulfil the die and to obtain the proper shape and dimensions of the forged piece. On some of areas of the forged piece the straining at the last blow is to small to cause the recrystallisation of austenite. For this pourpose a deformation of appr. 10 % is required (1,2). At lower deformation austenite grains grow by strain induced boundary migration. The AG growth gouverned by the temperature is relatively insignificant. That is confirmed in fig. 1, which shows that the austenite grain size is increased relatively little when the forging temperature is increased. In temperature controlled grain growth an exponential dependence temperature-AG size is observed (1,2). The influence of temperature is probably depressed by the fast cooling of the forgings. The microstructure in a controlled forged rod is lamellar pearlite and intergranular ferrite in areas of coarse and medium size AG, while in areas of small grains also some polygonal ferrite is present. The microstructure is an intimate mixture of clusters of coarse and fine austenite grains. That shows that the deformation of steel is very inhomogeneus ower the section of the rod. Fig. 1 shows that the difference between the minimal and the maximal AG size in the same section of the rod is appr. 3 ASTM grades and hardly dependant upon the forging temperature.

The microstructure of standard manufactured connecting rods is a dispersion of small cementite particles in a ferrite matrix, the AG size is much more homogeneus than in controlled forged rods because of the austenite transformation at heating the steel to austenitising temperature.

In steel A a pearlite ferrite microstructure with different AG size was obtained by one blow at forging different temperature.

In table 1 the properties of steel with a microstructure pearlite intergranular ferrite and different AG size are compared to that of the normalised steels with a microstructure lamellar pearlite and polygonal ferrite and to that of the heattreated steel with microstructure of small cementite particles dispersed in a matrix of ferrite. The comparison of data in table 1 shows that:

- the yield stress, elongation and notch toughness are higher in heat treated steel;
- the properties of normalised steel are similar to that of the steel forged to AG size 6-7;
- the elongation and notch toughness are significantly lower in the forged steel with AG size 2-3 grades than in normalised steel and in forged steel with AG size 6-7.

A discussion of the properties is given in another paper (2), it is however necessary to point out that the microstructure and the AG size influence only little, hardly significantly, the fatigue limit at rotative bending.

The fonction of connecting rods in automotive motor does not require a high cold deformability and a high notch toughness of the steel, for that reason acceptable mechanical properties were expected from controlled forged connecting rods, inspite of the poor homogeneity of AG ower the section. In table 2 the mechanical properties of both kinds of rods, controlled forged (rods A) and standard (rods B) are given. The yield force of rods A is appr. 60 % of that of rods B. The difference is significantly smaller by the rupture force, only appr. 10 % and the difference in elongation is in the error limit, therefore not significant. In fig. 3 the relationship number of cycles- load amplitude by the traction-compression test for both kinds of rods is given. At high load amplitude the endurance limit of controlled forged rods A is smaller than that of standard forged rods B. The difference diminishes when the load amplitude is decreased and at appr. 18 kN both kinds of rods show a virtually identical endurance of $2 \cdot 10^6$ cycles. It is again confirmed that the fatigue limit of controlled forged rods is virtually equivalent to that of standard rods, ev. small differences could be leveled balancing the composition of steel.

4. FRACTURE

The tensile fracture of rods B is small dimpled, ductile and transgranular with relatively rare coarse dimples grown on inclusions. Occasionally intergranular areas were observed on ridges inclined to the fracture plane. In rods A the tensile fracture depends upon the AG size. In coarse grained areas the fracture was mostly intergranular ductile, rarely transgranular and brittle. In areas of medium size and small AG the fracture was transgranular with a local morphology depending upon the angle between the propagating microcrack and the orientation of lamellas in pearlite (fig. 3). Large dimples were observed only around the inclusions. Frequent intergranular areas were observed on ridges inclined to the rupture planes. The intergranular surface was small dimpled where the crack propagated in intergranular ferrite and smooth where the crack progatated between ferrite and pearlite (fig. 4 and 5).

The fatigue fracture was similar in steel tested by rotative bending and by tension-compression. In rods B the fracture showed fatigue striation perpendicular to the direction of crack growth. Frequently the striation was assotiated with microcracks upright to the fracture plane. Rarely on inclined ridges connecting microcracks propagating in different planes intergranular areas were observed. On the fatigue fracture of controlled forged rods upright microcracks assotiated with striation and intergranular ridges extended in the fracture direction (fig. 6) were more frequent than on rods B. The general appearance of the transgranular fatigue fracture was similar to that reported by Gray et al. (3). Occasionally also in the fracture plane smooth areas without upright microcracks were observed (fig. 7), it is supposed that such areas are also produced by brittle intergranular crack growth. In coarse grained steel the fatigue fracture was similar, however intergranular areas were more frequent. On one rod the fracture initiation was found undamaged. It was intergranular (fig. 8). The striation was observed to initiate virtually immediately behind the intergranular area, it was however less ordered. Generally, more intergranular areas were observed on the fracture of rods A and no areas supposed intergranular were found in the main fracture plane of rods B. Otherwise on both rods the most of fatigue fracture was transgranular. It could be therefore concluded that the similarity of the fracture is consistent with the similarity in fatigue properties between the two types of rods.

5. CONCLUSION

With the aim to compare light die forgings standard and controlled forged automotive connecting rods were manufactured from suitable steels and investigated. The microstructure was a dispersion of cementite particles in ferrite in standard and lamellar pearlite-intergranular ferrite in controlled forgings.

Yield stress, notch toughness and elongation are lower in controlled forged steel, other mechanical properties are similar, newertheless fatigue limit by rotative bending and tension-compression tests is very similar. The morphology of the greater part of fatigue fracture is also similar, the difference due to the greater propensity of the pearlite-intergranular ferrite microstructure to intergranular crack propagation is not significant.

It could be concluded that the controlled die forging is a manufacturing process which offers comparable mechanical properties at significantly lower energy consumption than the standard forging.

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Table 1: Mechanical properties of the 0,48 C - 1,2 Mn - 0,28 Cr steel (steel A) with different microstructure

Microstructure[1]	M 1	M 2	M 3	M 4
Yield stress, N/mm^2	709	431	443	474
Rupture strength, N/mm^2	834	784	800	820
Elongation, %	28,7	22,5	21	15
Reduction of area, %	46,5	27	26,2	11,3
Notch toughness, J/cm^2	58	61,2	55,7	32,7
Hardness, HB	237	230	230	232
Fatigue limit[2], N/mm^2	386	365	335	348

1) M1 - heat treated steel with microstructure of cementite particle dispersed in a ferrite matrix;
   M2 - normalised steel with a microstructure of lamellar pearlite - polygonal ferrite;
   M3 - forged and controlled cooled steel with a microstructure of lamellar pearlite - intergranular ferrite and austenite grain size 6-7 ASTM grades;
   M4 - forged and controlled cooled steel with the same microstructure as M3 and austenite grain size 2-3 ASTM grades.

Table 2: Mechanical properties of test connecting rods

Rod	Hardness[1] HB on section I	II	III	Yield stress kN	Rupture force kN	Elongation %
A 1	254	240	238	53	85	7,2
A 2	259	240	240	51	83	7,4
A 3	232	226	238	52	85	7,1
B 1	219	220	223	81,5	91,7	6,5
B 2	225	225	235	82	92,1	6,4

1) - average of 5 measurements measured on the section of rods shown in fig. 1. The rods A 1, A 2 and A 3 were taken at the start, the middle and the end of controlled forging trials.

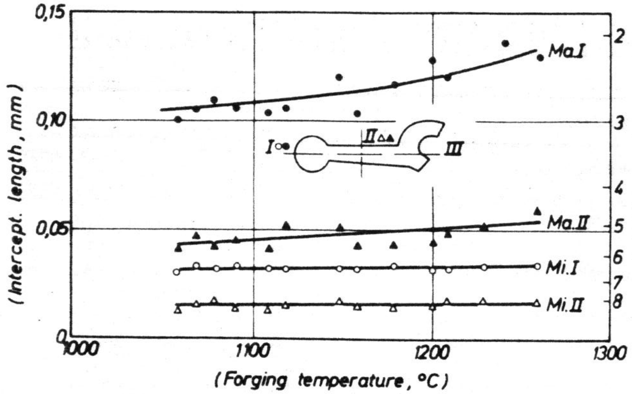

Fig. 1: Influence of forging temperature on minimal (Mi) and maximal (Ma) austenite grain size on two sections of controlled forged rods.

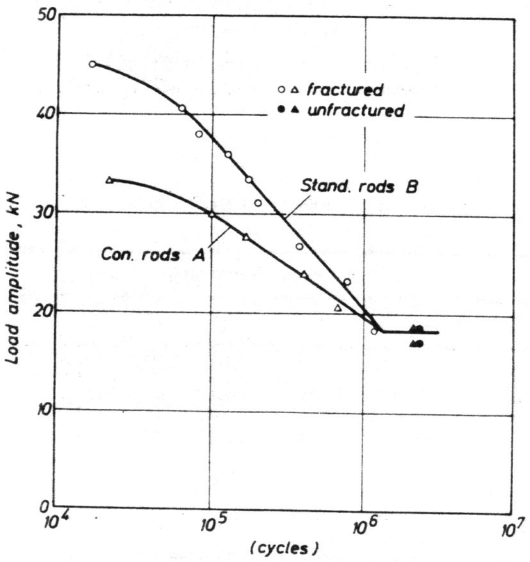

Fig. 2: Relationship number of cycles-load amplitude for controlled (A) and standard (B) forged connecting rods.

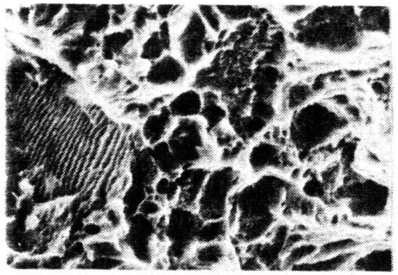

Fig. 3: magn. 3000 X.
Tensile fracture of controlled forged rod.

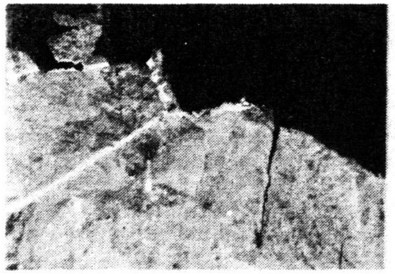

Fig. 4: magn. 200 X.
Section of the tensile fracture of controlled forged rod. Intergranular and transgranular crack propagation.

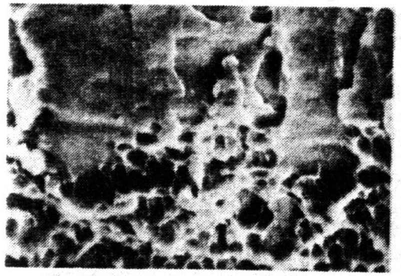

Fig. 5: magn. 3000 X.
Intergranular brittle and ductile crack propagation on the sample on fig. 4.

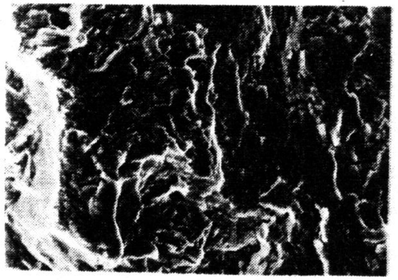

Fig. 6: magn. 1000 X.
Fatigue fracture of controlled forged rod. Transgranular and intergranular crack propagation.

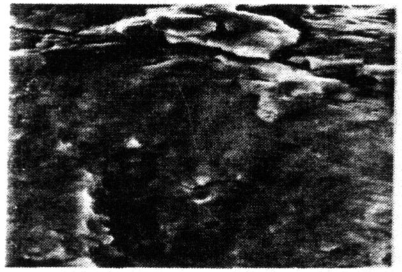

Fig. 7: magn. 2000 X.
Probable intergranular crack propagation on fatigue fracture of controlled forged rod.

Fig. 8: magn.1000 X.
Intergranular crack initiation of fatigue fracture of controlled forged rod.