MRL-R-985

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DEPARTMENT OF DEFENCE

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MELBOURNE, VICTORIA

REPORT

MRL-R-985

THE INFLUENCE OF FORGE REDUCTION RATIO ON THE TENSILE

AND IMPACT PROPERTIES OF A LOW-ALLOY ESR STEEL

G.M. Weston

Approved for Public Release

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ABSTRACT

The influence of hot forging reductions ranging from 1:1 (as-cast condition) to 20:1 on the tensile and notch impact properties of a low sulphur (0.002%) electroslag refined AISI 4340 grade steel has been investigated. Both properties achieved with the initial forging reduction of 1.5:1 were higher than the as-cast condition but lower than the values obtained with forging reductions of 2.5:1 and greater. The maximum level of mechanical properties attained with each forging reduction was found to be dependent on the amount of duplex grain structure present in the high temperature austenitic phase. Samples containing a higher percentage of duplex grain structure were also observed to require a faster quench rate to maximize the level of mechanical property. Small forging reductions of around 1.5:1 were considered insufficient to ensure the uniformity of deformation necessary to achieve a fine equi-axed austenite grain structure after hot working. Because of the low sulphur content, reductions of up to 20:1 had little influence on the anisotropy ratio of mechanical properties, in particular reduction of area and notch impact values.

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The influence of forge reduction ratio on the tensile
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ABSTRACT

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C O N T E N T S

THE INFLUENCE OF FORGE REDUCTION RATIO ON THE TENSILE

AND IMPACT PROPERTIES OF A LOW-ALLOY ESR STEEL

1.   INTRODUCTION

The electroslag remelting (ESR) process has established a world wide
reputation as a processing route for the production of premium quality wrought
steels, which compares favourably with those available through other secondary
remelting processes.

Due to the excellent homogenity, cleanliness and soundness of as-
cast ESR ingots, recent interest has centred around the utilization of ESR
material in the as-cast condition for both ordnance and industrial
applications [1,2,3,4]. In general, this work has been encouraging in that
the tensile and notch impact properties reported for the as-cast ESR material
have approached the values obtained for the wrought condition [3,4,5].
Furthermore, in studies of low-alloy ESR steels for gun barrel applications,
little difference has been observed in the fatigue and fracture toughness
properties before and after forging [5,6].

To capitalize on this potential, research has been directed towards
the production and evaluation of electroslag as-cast (ESC) components, with
the view of lowering the processing costs and obtaining improved material
utilization [1,2,4,5]. Examples of components produced hitherto reflect the
versatility of the process and include the manufacture of gears [3], valve
bodies and shaped turbine components from hard-to-work nickel and cobalt base
alloys [1]. The development of techniques for the production of ESC hollows
has enabled the production of seamless corrosion-resistant tubing for use in
the chemical industry [1,6]. ESC hollows have also been used as starting
blanks for the production of gun barrels with the view of lowering production
costs by reducing forging times and eliminating the need for trepanning solid
forgings [8].

Evaluation of the mechanical properties of ESR rotary forged gun
barrels, however, has revealed a severe drop in tensile and notch impact

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values when the starting blanks were only lightly worked, involving forging reductions of less than 1.2:1 [8,9]. A similar dependence of properties on the forging ratio has also been observed with solid ESR ingots which have undergone reductions of 1.2:1 [10]. Klein et al [9] reported the presence of a duplex grain structure in lightly worked sections and considered that this was responsible for the sharp drop in properties. Another possible explanation for this phenomenon is that small reductions may open up voids around inclusions which would have subsequently healed with further hot working.

As only two commercial ingot sizes are at present available within Australia to cover all applications, forging reductions in some instances may of necessity be restricted to levels approaching the above critical range. This paper investigates the extent to which both tensile and notch impact properties are impaired and defines the hotworking range over which this phenomenon occurs. The ESR steel investigated was a low sulphur (0.002%) AISI 4340 grade in the heat treated condition. Attention is also directed toward identifying microstructural differences which may account for a change in mechanical property behaviour.

2. EXPERIMENTAL

The present work used an as-cast ESR disc 625 mm in diameter and 600 mm in length which had been removed from the bottom end of a large commercial ingot 2000 mm in length.* The composition of this material (Table 1) closely matched material supplied locally for gun barrel manufacture. Forging was undertaken in a way which enabled mechanical property evaluation at a number of different forging reductions ranging from 1:1 (ie as-cast) to 20:1 (shown in Fig. 1). After forging, a specimen disc 130 mm thick was removed from the central position of each stepped section. Tensile[+], notch impact and compact tension[†] specimen blanks were removed from close to the mid-radial position of each disc (Figs. 1 and 2). With forging reductions above 5:1, this layout was modified to match the smaller disc diameters.

Specimen blanks 20 mm square and 110 mm long were heated to 860°C for one hour, oil quenched and then tempered at 580°C for two hours. This treatment resulted in a hardness of 400 to 412 HV30. Tensile tests were

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* This material was received at MRL in November 1980 from Electrometal, Brazil.

+ Specimen dia 9 mm gauge length 42 mm.

† The fracture toughness and fatigue data generated from these compact tension specimens will be the subject of a second report.

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conducted at room temperature (RT) while notch impact tests were carried out at RT and -40°C. Results were based on a minimium number of three tests.

Several tensile and notch impact specimens with longitudinal orientations, taken from the 1.5:1 and 5:1 forge reductions were given a heat treatment to achieve grain refinement [11]. This involved heating specimens rapidly to 800°C and immediately quenching as outlined in Fig. 3. All specimens were finally given the same hardening and tempering heat treatment previously outlined.

Metallographically prepared longitudinal sections of broken tensile specimens were etched in Saspa Nansa reagent to above 60°C to reveal the prior austenite grains boundaries. Grain size estimates were undertaken using an optical attachment which incorporated standard chart overlays.

3. RESULTS

Tensile and notch impact values for both the longitudinal and transverse directions at each level of deformation ratio are given in Table 2, and shown graphically in Fig. 4. Comparative tensile and notch impact values for two deformation ratios (1.5:1 and 5:1) before and after a grain refining heat treatment are given in Table 3 and shown graphically in Fig. 5.

3.1 Mechanical Properties of As-cast and Forged Material

From the mechanical property values in Table 2 and Fig. 4, it is evident that, irrespective of test direction, values for 0.2% proof stress, reduction of area, elongation and notch impact toughness of the initial 1.5:1 forge reduction were in most instances intermediate between the as-cast values (lower) and the values obtained with forging reductions of 2.5:1 and more (upper values). The one exception was the lower longitudinal notch impact value for the 1.5:1 reduction ratio which was slightly below the as-cast value and similar to the generally lower notch impact values obtained with the two largest reductions for both test directions. By comparison, tensile strength for the 1.5:1 reduction was unaffected and matched closely values obtained after further forging.

There was also a much smaller but consistently discernible drop in the longitudinal proof stress and reduction of area values for the 5:1 forge ratio when compared with the comparatively uniform results obtained with the neighbouring forging reductions of 2.5:1 and 10:1. The drop in both these properties was even smaller with the corresponding transverse samples.

It was observed that the mechanical properties reported above for the 1.5:1 reduction were extremely sensitive to quenching conditions. The aforementioned properties were attained using small partially machined sample

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sizes and vigorous agitation within a fast quenching oil medium. The normal
blank size with minimal agitation resulted in a severe drop in all properties
with the exception of tensile strength which increased. In most instances
the value of mechanical properties obtained were below comparable as-cast
values. The 5:1 forge ratio showed a smaller sensitivity to quenching
procedure while no quenching sensitivity was evident for the remaining forging
reduction.

3.2 Mechanical Properties of Material Forged to Reductions of 1.5:1 and 5:1 and then Grain Refined

It is evident from the values in Table 3 and Fig. 5 that following
grain refinement, the mechanical properties of both the 1.5:1 and 5:1 forging
reductions had been restored to levels either equivalent to or slightly above
the comparatively uniform property levels reported earlier for the
neighbouring forging reductions of 2.5:1 and 10:1. The properties obtained
after grain refinement were similar irrespective of whether one or more grain
refining cycles were given.

3.3 Stress-Strain Behaviour Before and After Grain Refinement

Stress-strain behaviour illustrated in Fig. 6 shows that a common
base curve was obtained for the three forging reductions (2.5:1, 10:1 and
20:1) which returned a uniform level of mechanical properties, while different
curves were obtained for the 1.5:1 and 5:1 reductions where a lower level of
mechanical properties was observed. The forging reduction with the largest
deviation from the base curve (1.5:1) was coincident with that showing the
largest drop in the level of mechanical properties. On retesting grain
refined specimens from the 1.5:1 and 5:1 forging reductions the stress-strain
behaviour was restored to an identical level as the other forging ratios (Fig.
7).

3.4 Influence of Forge Ratio on Anisotropy of Mechanical Properties

The small variation in anisotropy ratio over the entire hot working
range, illustrated in Fig. 8, shows that with the present clean ESR steel
(0.002%S) there was little deterioration in transverse reduction of area and
impact toughness values even with forging reductions approaching 20:1.
Anisotropy of proof stress values was not influenced by hot working.

3.5 Microstructure

The prior austenite grain structure for each forging reduction after
final heat treatment is shown along with the matching microstructure in Figs.
9 and 10.

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3.5.1 As-Forged Microstructure

Microstructural examination of tensile specimens taken from the
1.5:1 forge reduction which displayed considerably lower tensile and notch
impact values revealed a prior austenite dulpex grain structure consisting of
bands of coarse elongated grains (ASTM 8-9) in a matrix of finer grains (ASTM
10-11). An estimated 30 to 40% in area of microstructure was apportioned to
these bands of coarse elongated grains which can be observed in the upper half
of the appropriate field shown in Fig. 9. In contrast to the finer grains,
the bands of coarser grains were always restricted to within the lighter
etching regions of the microstructure.

Some duplex grain structure was observed with all forging reductions
above 1.5:1. However, in these instances the duplex grain structure consisted
of small isolated pockets of equi-axed coarse grains (ASTM 8-9), dispersed
through a fine grained matrix (ASTM 11). The pockets of coarse grains were
again confined within the lighter etching areas. The area occupied by the
coarse grains appeared greater for the 5:1 reduction, being estimated at 15 to
20% compared with 10% for the remaining three reductions. A quantitative
grain assessment was difficult to achieve in the present work as the etching
response was inconsistent.

There did not appear to be any discernible difference in the
matching tempered martensitic microstructures of above tensile specimens as
shown in Fig. 10.

3.5.2 As-Cast Microstructure

In comparison with the forged microstructures, the as-cast grain
size was uniformly larger and in the ASTM size range 8-9.

3.5.3 Grained Refined Microstructures

After grain refinement, some duplex microstructure still persisted
in the two forging reductions (1.5:1 and 5:1). The microstructure for both
these reductions now closely matched that of the remaining three reductions
not given this heat treatment (Fig. 11). Even after two or more grain
refining cycles some duplex grain structure still persisted.

4. DISCUSSION

It is considered from the present results that the main factor
influencing the lower tensile and notch toughness values for the 1.5:1 forge
ratio was the presence of coarse grained areas within an otherwise fine
grained equiaxed matrix, i.e. a duplex grain structure. The same argument is
given for the much smaller drop in properties for the 5:1 forge reduction.
There was no discernable difference between the tempered martensitic

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microstructures of any forging reduction. It is considered that the lower tensile and notch impact properties and marked variability in quenching response observed with the 1.5:1 reduction ratio will only be overcome providing that the material is forged beyond a critical reduction level of 1.5:1. Above this level of forging a more evenly deformed ingot structure is achieved overcoming the problem of isolated pockets of lightly worked as-cast grains remaining after recrystallization. In this respect, the present work supports the findings of Venal et al. [8] who concluded that a duplex grain structure was responsible for the severe drop in mechanical properties observed with forging reductions of less than 1.2:1.

The percentage of duplex grain structure present within the microstructure was observed in the present work to influence the maximum level of mechanical properties attained; the higher the percentage of coarse grained areas within the microstructure, the greater the drop in the level of tensile and notch impact values obtained. Even after allowing for possible errors in grain area estimates and inconsistencies in etching response reported earlier, a clear trend was evident. The three forging reductions with an estimated 10% duplex grain structure present always returned uniform and consistently high mechanical properties regardless of slight variations in quenching procedure. However, for the 5:1 reduction where only a small drop in some tensile values was observed, similar grain area estimates were closer to 20% and this figure approached 40% for the 1.5:1 reduction where both tensile and notch impact values were noticeably lower. This trend was also reflected in the stress-strain behaviour of the above two forging reductions. The stress-strain curve for the 1.5:1 samples showed a greater deviation than the corresponding 5:1 samples when compared with the base curve established with the remaining three forge ratios. After grain refining samples from both the 1.5:1 and 5:1 forging reductions, the microstructures, stress-strain behaviour and mechanical properties associated with all forging reductions were similar. It would appear therefore, that a decrease in the amount of duplex grain structure in the grain refined samples was mainly responsible for the restoration of mechanical properties and assimilation of stress-strain behaviour for all levels of forging. Sonomoto and Okada [12] also found an increase in the percentage of duplex grain structure to influence the impact strength of a 0.54% carbon steel (S53C). Their results showed that the impact strength of a fine grained steel decreased as the area occupied by coarse grains approached 50%. As this percentage of coarser grains was progressively increased beyond this level, a concomitant increase in notch impact strength was observed thus reversing the previous trend. From this work, the impact properties of a uniformly coarse grained steel could be expected to approach that of a similar forged steel with a large percentage of duplex grain structure present. This would explain why the sound uniformly coarser grained as-cast material in most instances returned notch impact values approaching or above that for the 1.5:1 reduction.

Increasing the percentage of duplex grain structure also increased the likelihood of a slack quench during subsequent heat treatment, which would lead to a marked drop in tensile and notch impact values. Where there was an increase in sample size and reduced quench agitation performed on samples from the 1.5:1 forging reduction, both tensile and notch impact values fell dramatically to a level often well below the comparable value of mechanical property for the as-cast condition. Under similar quenching conditions a lowering of some mechanical properties was noticeable with the 5:1 reduction

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ratio but these changes were never severe while no similar quench sensitivity was observed with the remaining reduction ratios.

The reason why increasing the percentage of coarse grained areas should influence the quench sensitivity is not clearly understood as AISI 4390 grade steel has a very large hardenability and would be considered relatively insensitivity to quench rate. However, it is known that increasing the grain size raises the M_s temperature resulting in coarser martensite with a consequential lowering of strength and toughness [13]. Hawkins [14] has suggested that a satisfactory quench procedure for this steel should result in a proof stress/tensile strength ratio of 0.9. However, regardless of quench severity this ratio was not achieved with the 1.5:1 or longitudinal 5:1 forging reductions. The increased sensitivity to quench rate experienced here for the two forging reductions having the greater percentage of coarse grained areas may explain the marked variability in the severity of the drop in tensile and notch impact values reported in the literature for small forging reductions of up to 1.5:1 [8,9,10].

As recrystallization and grain growth are a complex phenomena in steel, it is only possible to generalize on the main factors influencing the formation of a duplex grain structure. It is known however, that a certain minimum amount of hot work is necessary to ensure that areas of undeformed or unevenly worked structure are removed by forging [15]. Failure to achieve this minimum level of deformation would promote non-uniform recrystallization and hence the formation of a duplex grain structure. This explanation would appear to account for the elongated bands of coarse grains observed in an otherwise fine grained matrix with samples taken from the smallest forging reduction of 1.5:1. In this instance a forging reduction of 1.5:1 apparently was not sufficient to uniformly deform the ingot section and hence bands of lightly worked ingot structure did not recrystallize after hot working. With such small reductions, a commonly practiced pattern of forging of several small steps compared with one large, one could in fact aggravate the situation. This factor may have been responsible for the slight percentage of duplex grain structure associated with the 5:1 forging reduction.

Another factor known to influence the uniformity of recrystallization is the degree of segregation within the ingot. Higher concentrations of solute elements particularly carbon, aluminium and inclusions such as Al_2O_3 have been observed to retard recrystallization compared with the purer zones [15]. In effect this means that for the same annealing time, the range of critical stress for the more heavily segregated zones is displaced towards higher strain. As areas of coarse grains in the present metallographic sections were only observed within the lighter etching regions, indicative of higher concentrations of solute atoms, solute segregation may have been a factor underlying the small amount of duplex grain structure observed with all forging reductions. Thus with small forging reductions of < 1.5:1 ingot segregation could be expected to influence the uniformity of deformation in addition to having a retarding influence on the the recrystallization process.

Given the complexities of the recrystallization process, it is difficult to account for the persistence of a small amount of duplex grain structure at all levels of forging above the 1.5:1 reduction ratio and, in

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particular, the greater amount associated with the forging reduction level of 5:1. In this instance, the production of a step forging with designated reduction ratios and limited material may have influenced the usual forging pattern with a few large deforming steps to break-up the ingot structure being replaced in some instances by several smaller ones. Similar small duplex microstructure variations present may account for unexplainable mechanical property inconsistencies often observed between otherwise similar steels.

Only small variations in anisotropy ratio with increased deformation were observed in the present work for longitudinal and transverse notch impact and reduction of area values. As the anisotropy associated with both these properties is known to be sensitive to inclusion content, especially sulphides as deformation ratio is increased, the present results are considered to reflect the inherent chemical uniformity, structural homogenity and cleanliness of this material. The present result for a steel containing 0.002%S was not unexpected, as published data [16] has suggested that sulphur levels less than 0.004% are sufficient to eliminate marked mechanical property anisotropy over an extended hot working range.

5. CONCLUSIONS

1. A duplex grain structure was considered responsible for the lower tensile and impact toughness values recorded with the smaller reduction of 1.5:1 and the small drop in some tensile values observed with the 5:1 forging reduction.

2. An interrelationship was observed between the fraction of microstructure occupied by coarse grains, the magnitude of the decrease in tensile and notch impact values, and the care needed during quenching to maximize these properties.

3. One grain refining cycle was sufficient to restore the tensile and notch impact values for both the 1.5:1 and 5:1 reductions to the level obtained with the remaining forging reductions.

4. Little mechanical property anisotropy was observed with this very low sulphur (0.002%) steel with forging reduction ratios of up to 20:1.

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TABLE 1

COMPOSITION OF ESR STEELS

Steel used in the present investigation (Electrometal)
compared with representative Australian ESR steel
for ordnance applications

SOURCE	ELEMENT									
	C	Si	Mn	S	P	Ni	Cr	Mo	V	Al
Electrometal	0.43	0.47	0.70	0.0014	0.009	3.3	1.2	0.70	0.15	0.013
Local EN-25 Grade	0.33	0.26	0.64	0.005	0.02	2.58	0.65	0.50	-	-

Amounts are in wt%.

TABLE 2

TENSILE AND CHARPY IMPACT VALUES FOR EACH
FORGING REDUCTION AND TESTING DIRECTION

LONGITUDINAL PROPERTIES

Forge Ratio	0.2% Proof Stress MPa	Tensile Stress MPa	Reduction in Area %	% Elong	Fracture* Stress MPa	Charpy Impact J	°C
						23	-40
AS-CAST	1130	1258	22	8	1490	38	20.5
1.5:1	1158	1345	50	13	2017	37.5	23
2.5:1	1224	1356	55.5	15	2115	47	28
5:1	1185	1355	51	14	2150	42	24.5
10:1	1219	1345	53	13.9	2051	37	21
20:1	1266	1397	56.7	14.3	2172	34	24

TRANSVERSE PROPERTIES

Forge Ratio	0.2% Proof Stress MPa	Tensile Stress MPa	Reduction in Area %	% Elong	Fracture* Stress MPa	Charpy Impact J	°C
AS-CAST	1143	1230	29	8.5	1610	28.5	15.5
1.5:1	1160	1348	45.5	12.5	1995	35	22
2.5:1	1210	1344	49	13.9	1987	42	29
5:1	1209	1342	47.5	13	1944	39	24.5
10:1	1228	1339	47.6	12.7	1955	38	21.5
20:1	1228	1391	47	13	2053	30.5	20

* Fracture Stress = $\dfrac{\text{Fracture Force}}{\text{Fracture Area}}$

TABLE 3

TENSILE AND CHARPY IMPACT VALUES FOR TWO LONGITUDINAL

FORGING REDUCTIONS AFTER GRAIN REFINEMENT

Forge Ratio	0.2% Proof Stress MPa	Tensile Stress MPa	Reduction in Area %	% Elong	Fracture Stress MPa	Charpy Impact J 23°C
1.5:1	1218 (1158)	1373 (1345)	52 (50)	15 (13)	2051 (2017)	44 (37.5)
5:1	1246 (1185)	1392 (1355)	56 (51)	15 (14)	2168 (2150)	40 (42)

( )   Original values prior to grain refinement.

SPECIMEN DISC 130mm THICK

1:1   1.5:1   2.5:1   5:1   10:1   20:1

SPECIMEN PLANE   FOR TENSILE &
CHARPY V-NOTCH IMPACT SPECIMENS

SPECIMEN DISC 130mm THICK

SEGMENT FROM
SPECIMEN DISC
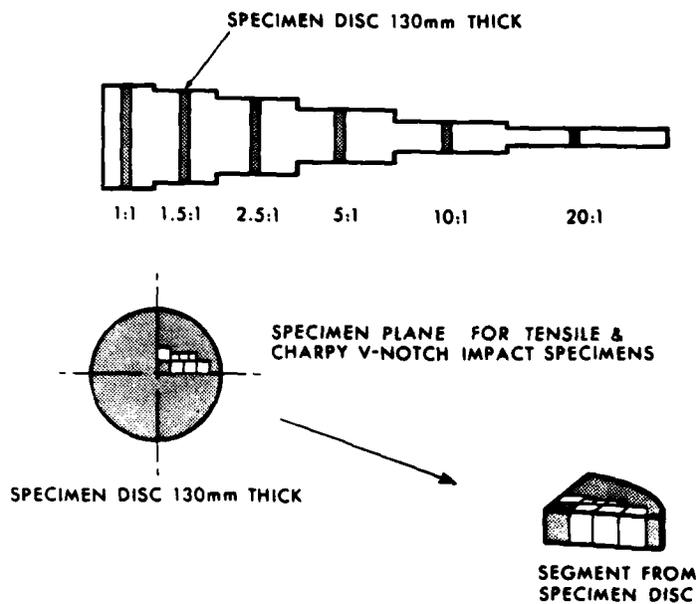
FIGURE 1.   Step forging of ESR ingot showing the reductions undertaken,
position of specimen discs and specimen layout on segment of this
disc.   Charpy blanks are the smaller.

LONGITUDINAL, TENSILE & CHARPY
SPECIMEN

TRANSVERSE
TENSILE
SPECIMEN

LONGITUDINAL,
C.D.S. SPECIMEN

TRANSVERSE C.T.S. SPECIMEN

TRANSVERSE
CHARPY
SPECIMEN
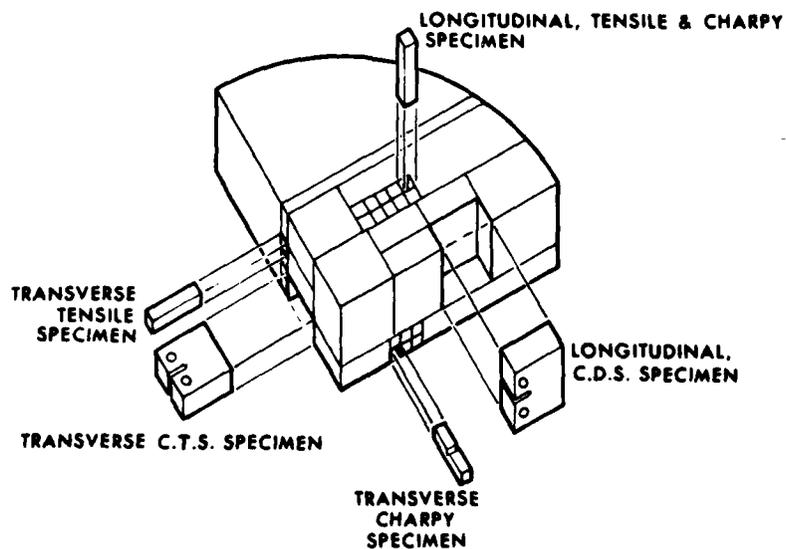
FIGURE 2.   Detailed specimen layout on segment of specimen disc.
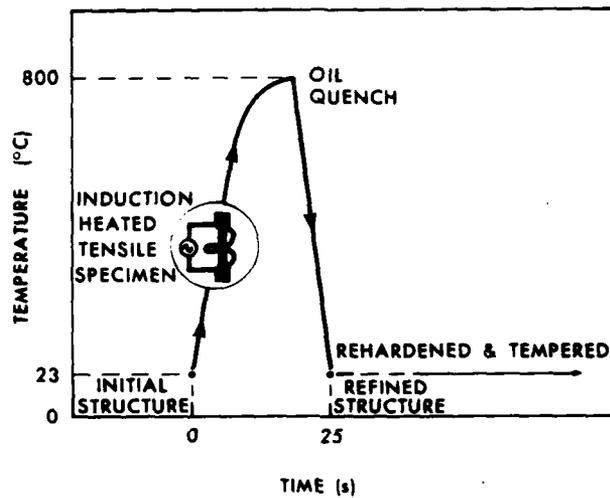
FIGURE 3.   Heat treatment cycle followed to bring about grain refinement in
            tensile and notch impact specimens.
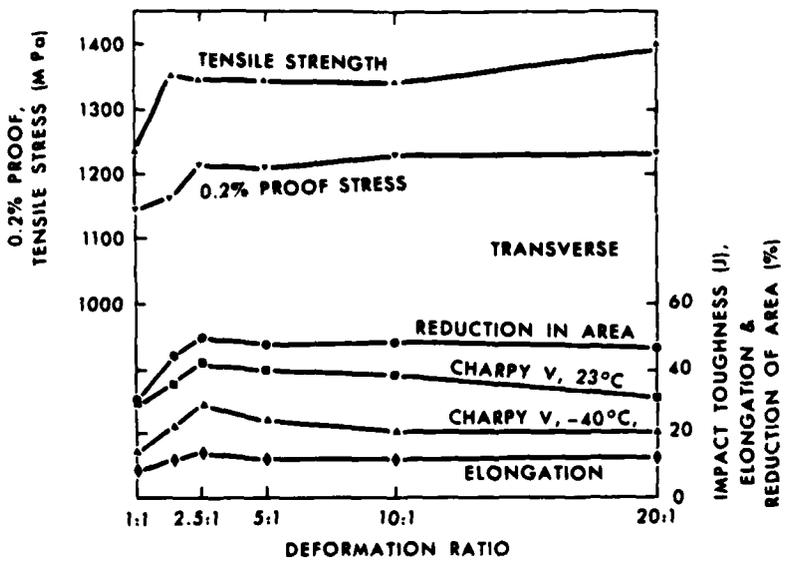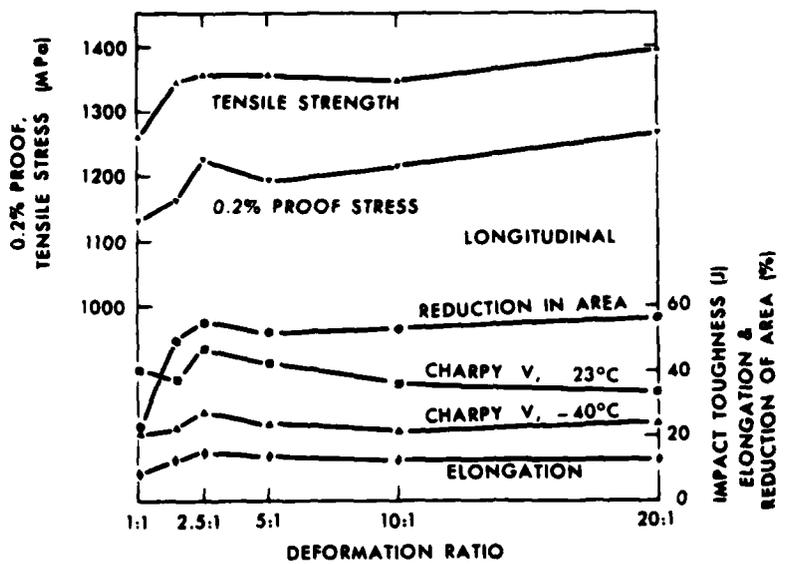
FIGURE 4.   Influence of deformation ratio on the longitudinal and transverse
tensile and notch impact properties of low sulphur ESR steel.
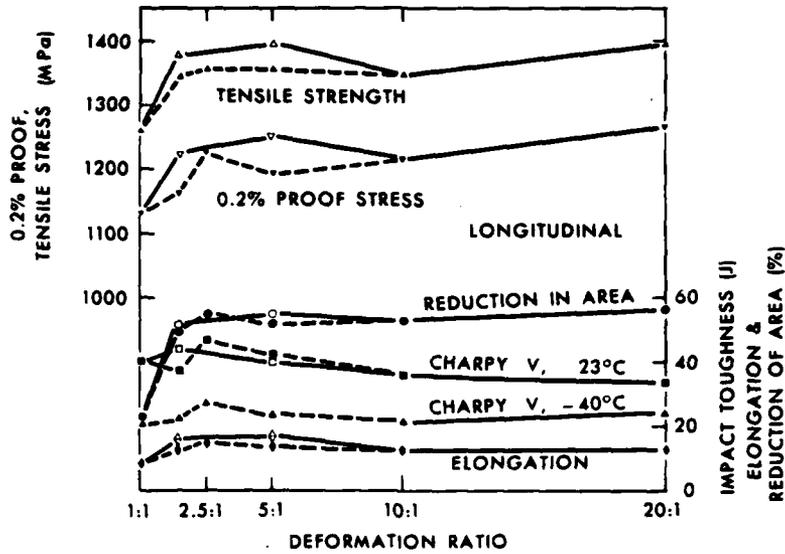
FIGURE 5.   Comparative longitudinal tensile and notch impact values for two
             deformation ratios (1.5:1 and 5:1 open symbols) after grain
             refinement. Solid lines show new curves following grain
             refinement while dotted segment illustrates the curves for
             original values represented by solid symbols.
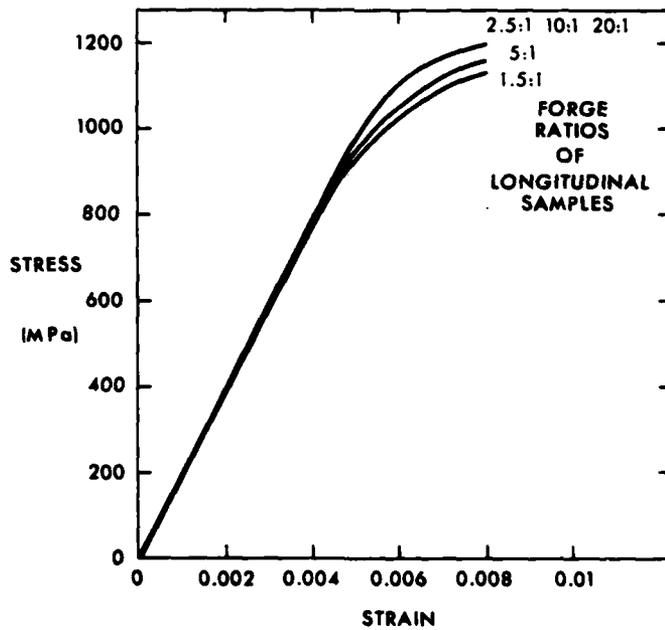
FIGURE 6.   Stress-strain relationship for each forge ratio showing the
             different behaviour for two deformation ratios (1.5:1 and 5:1)
             which also displayed lower tensile and notch impact properties.
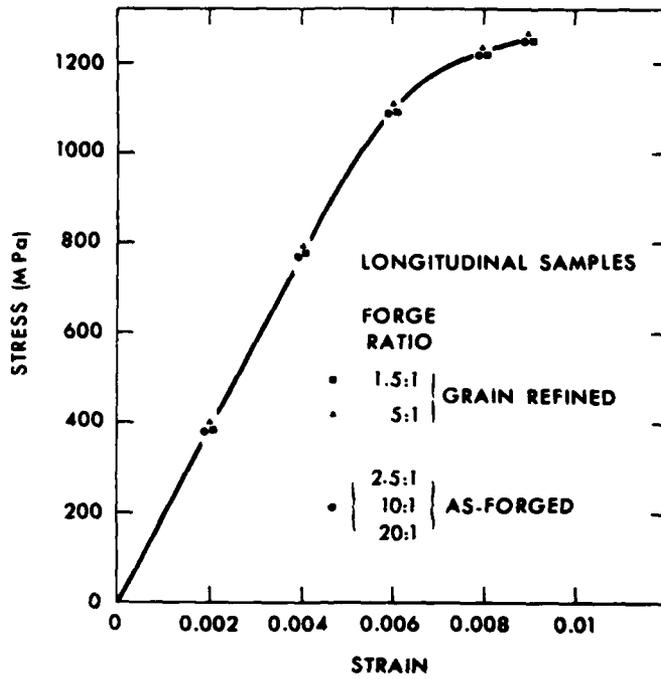
FIGURE 7.   The above curve shows that after grain refinement, the stress-strain behaviour for the 1.5:1 and 5:1 reductions followed the basic curve established earlier for the remaining three reduction ratios.
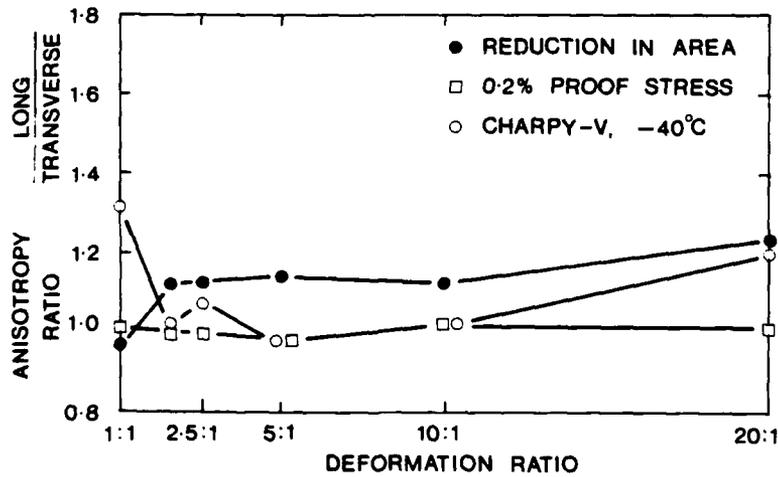
FIGURE 8.   Influence of deformation ratio on the anisotropy ratio.
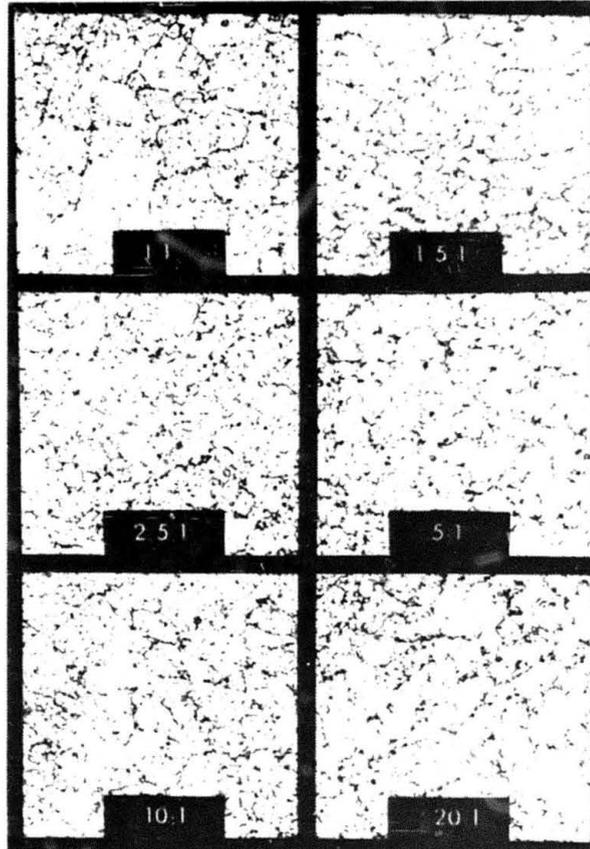
FIGURE 9.   A set of broken transverse tensile specimens sectioned
             longitudionally and etched to reveal the prior austenite grain
             structure.   All specimens were in the hardened and tempered
             condition.   X500
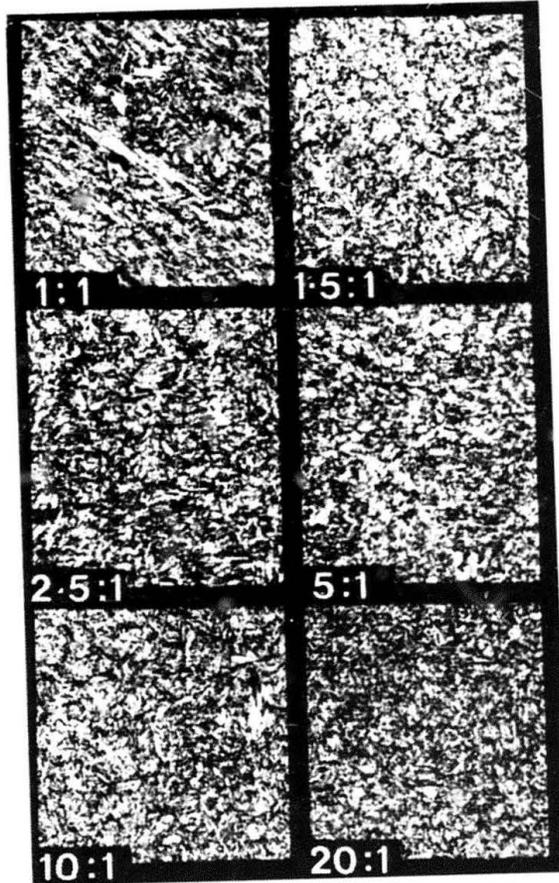
FIGURE 10.   The tempered martensitic microstructure of the above broken
              transverse tensile specimens after etching in 2% nital. X500.
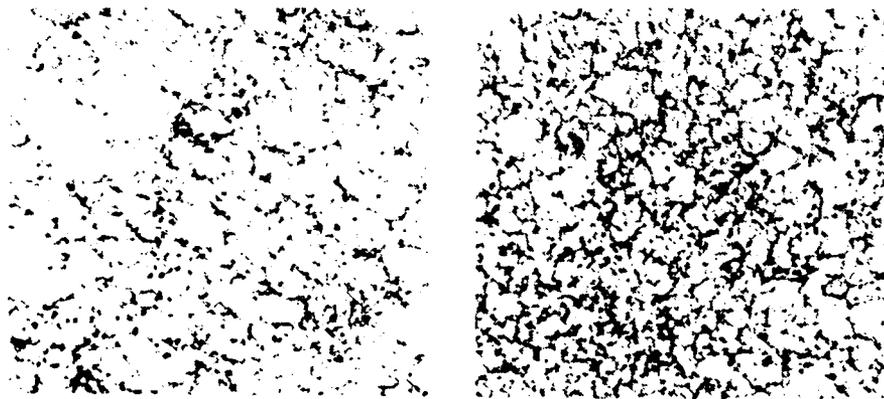
FIGURE 11.   (a)   Microstructure of Heat treated longitudional tensile
specimen following a forging reduction of 1.5:1, showing
the duplex prior austenite grain structure.   X500.

(b)   Microstructure of a similar tensile specimen after
grain refinement showing the uniformly finer and more
equi-axed grain structure.   X500.