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Some Important Properties of Gas Pipeline Steels

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ABSTRACT

This paper has briefly summarised some of the major developments in high-strength, low-alloy (HSLA) steels, with particular reference to the steels used in the Gas Industry. Gas pipeline steels should have adequate strength, toughness (i.e. resistance to brittle and ductile fracture propagation) and weldability. By producing normalised or controlled rolled steels with low carbon contents and fine grain sizes the requirements of strength, resistance to brittle fracture and weldability can easily be met. Further if the steel has undergone into some form of sulphide modification treatment it will attain adequate resistance to ductile fracture propagation.

1. INTRODUCTION

The discovery of natural gas in the districts of Sylhet, Comilla, Noakhali and Chittagong is probably the most important factor in the development of many of the Bangladesh Industries in recent years. In order to move the gas to the rest of the country, it is necessary to construct a bulk transmission system. British gas transmission system consists of more than 8,500 miles of pipeline and the total length of American gas transmission system in service is well in excess of 200,000 miles [Jones (1989) and Weiner et al]. The gas pipe steel used for transmission is required to withstand high pressure ranging from 100-1000 psi while the pipe for distribution is required to withstand less than 100 psi. The pipes are generally in the range 24-36 inch in diameter, although gas pipes of 42 inch and 48 inch diameter are now available.

In order to achieve the economic transmission of large quantities of gas to the rest of the country, it is necessary to use high pressure levels - British Gas uses a maximum working pressure of 1000 lbs/in^2 [Whiteman (1978)]. The steel pipelines must therefore meet specific requirements if the system is to operate safely and effectively.

2. PROPERTIES

The steel pipes must have adequate:

2.1 Strength
2.2 Toughness
2.3 Weldability

2.1 **Strength:** The steel linepipe must have an adequate strength to withstand the high gas pressure without rupturing. The maximum operating stress is in the hoop direction and therefore all specimens (tensile,Charpy,etc) are taken transverse to the pipe axis (as shown schematically in Figure 1). The pipeline steels are designated by X-grade - This means that an X52 steel has a minimum specified yield stress of 52 Ksi (52000 psi). This is a vital parameter as it is the basis of the maximum permissible operating condition of a pipeline [Gas Engineers (1976), ASME (1968)].

2.2 **Toughness:** Unfortunately the safe operation of pipelines is not guaranteed by ensuring adequate levels of strength since pipes can contain various notches and imperfections (particularly at welds) and these must be taken into account. A notch is important in an engineering structure because the stress and strain become concentrated at the notch tip (Fig. 2). Thus, even though the structure may be loaded well below its yield stress, the concentration of stress and strain at the notch top may be sufficient to produce fracture from the notch.

The nature of the fracture is temperature dependent because steel undergoes a ductile-brittle transition. The Charpy test can be used to demostrate this phenomenon. If the amount of energy needed to fracture the Charpy specimens is plotted against the temperature at which the specimens were fructured, a curve of the type shown in Figure 3 can be constructed. It can be seen that as the temperature is reduced, the energy needed to fracture the specimens decreases. This behaviour leads to the concept of a transition temperature, above which the material behaves in a ductile manner and below which the material behaves in a brittle manner. The reason for this change of behaviour is that the mode of fracture

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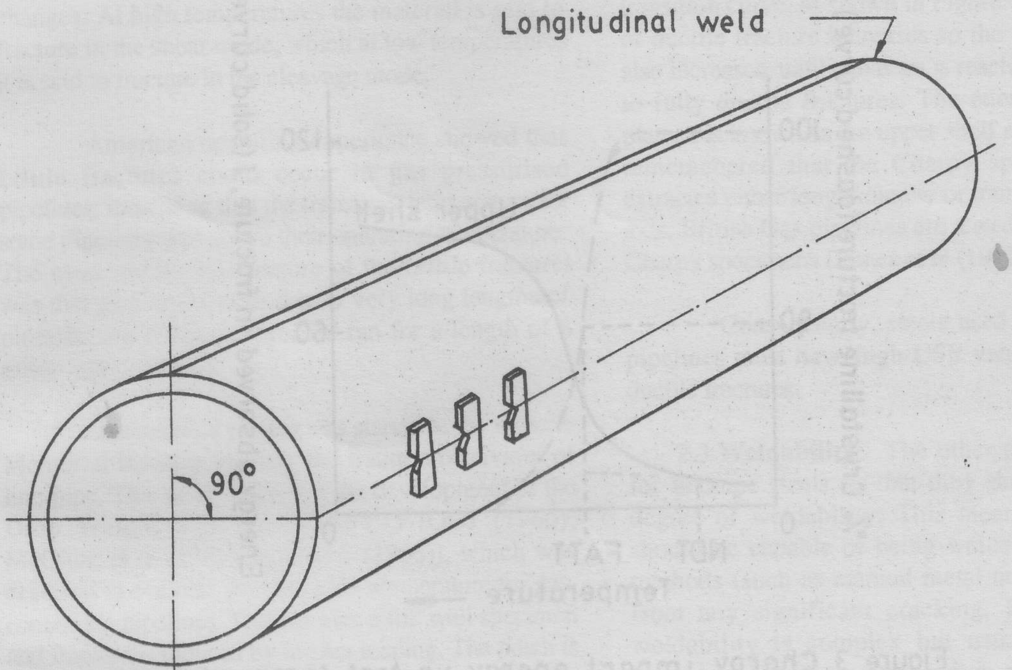

Figure 1 Extraction of test specimens from a linepipe

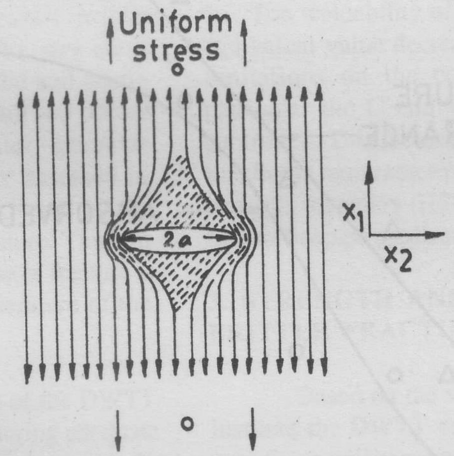

Figure 2 Schematic representation of the stress/strain Concentration around a crack tip.

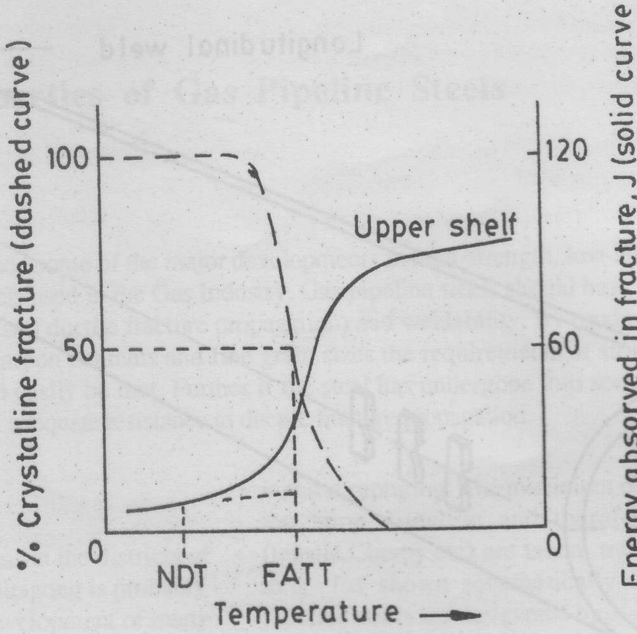

Figure 3 Charpy impact energy vs test temperature

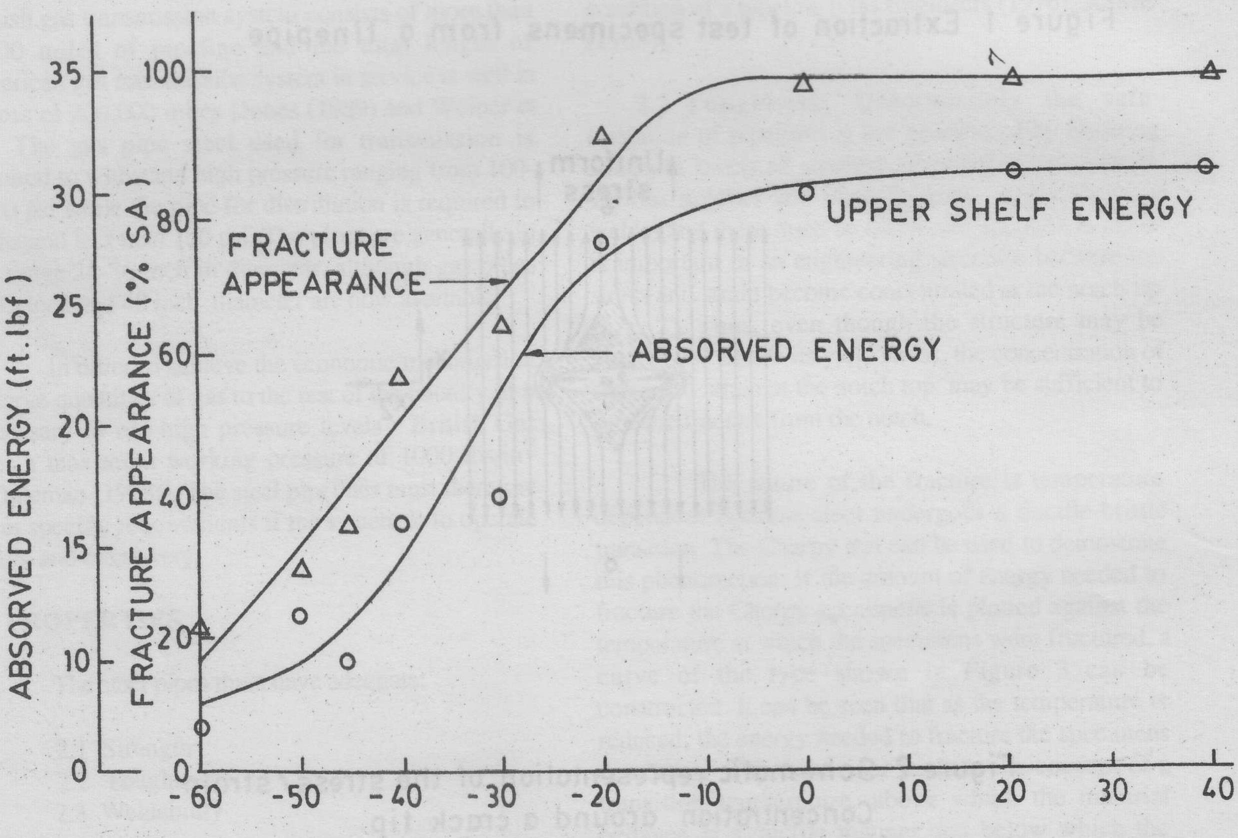

Figure 4 The measurement of an USE Value from a Charpy curve

changes. At high temperatures the material is said to fracture in the shear mode, which at low temperatures it is said to fracture in the cleavage mode.

American operating experience showed that brittle fractures could occur in gas pressurised pipelines, indicating that the transition temperature for some pipelines was above their operating temperature. The most unfortunate feature of the brittle fractures was that they could extend over very long lengths of pipeline, the longest on record ran for a length of 8 miles [OGJ (1960)].

As a result, a project was started at the Battelle Memorial Institute to study the fracture behaviour of line-pipe. This work resulted n the development of the Drop Weight Tear Test (DWTT) [OGJ (1960), McClure et al (1965) and AGA (1966)], which was designed to evaluate the transition temperature for gas-containing pipelines. The test uses a full wall specimen and fracture is induced by impact loading. The notch is pressed into the edge of the specimen and this introduces a small region of cold worked material thereby ensuring that the fracture initiates in a brittle manner.

The object of the test is to find the temperature at which the specimen will not support brittle fractures. The test therefore utilises the very clear difference in appearence between ductile and brittle fracture surfaces. Ductile fractures are dull and fibrous while brittle fractures have a brighter, granular appearance. The results of the test are assessed in terms of the area of fracture surface covered by the ductile (shear) mode at the test temperature. Thus, in the Battelle test, the area of the shear type of fracture is measured and plotted against the temperature of the test.

Unfortunately, the introduction of the DWTT did not finally resolve the matter of ensuring adequate level of toughness. In 1969, two long but completely ductile fractures occurred in the U.S.A. [AGA (1969)] and it became necessary to study the factors governing the resistance to ductile failure. Full scale pipe tests were carried out as part of this programme. This work showed that there was an empirical relationship between the resistance to propagating ductile fractures and the Charpy upper shelf energy (USE). The USE value is determined from a Charpy transition curve, as shown in Figure 4. As the amount of ductile fracture increases so the energy absorbed also increases, until a plateau is reached corresponding to fully ductile fractures. The energy level of this plateau is known as the upper shelf energy. It must be rememebered that the Charpy specimens can be extracted either longitudinally or transverse to the pipe axis. British Gas pipelines are tested using transverse Charpy specimens [James et al (1971)].

Consequently, steels used for transmission pipelines must have high USE values to avoid long ductile fractures.

2.3 **Weldability:** The other main requirement for linepipe steels is that they should have a high degree of weldability. This means that the pipes should be capable of being welded using low cost methods (such as manual metal arc) and not suffer from any significant cracking. Determination of weldability is complex but usually the welding procedure is based on the carbon equivalent. This is given by a formula of the type:

$$\% \text{ Carbon equivalent} = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15$$

The weldability of steel improves as the carbon equivalent value decreases and this imposes certain limitations on the composition of the steel. In particular the C and Mn levels must be carefully controlled. This factor (together with the strength and toughness requirements) means that steels of the high strength, low alloy (HSLA) type are the most suitable for gas linepipe applications.

3. STRENGTH AND THE RESISTANCE TO BRITTLE FRACTURE

Based on the work of the Battelle Memorial Institute the DWTT was adopted for the purpose of specifying resistance to brittle fracture. A statistical analysis of available DWTT data showed that a satisfactory level of safety could be achieved by calling for a test temperature of $0^{o}C$, and requiring each DWTT specimen to show a minimum of 75% ductile fracture (sometimes known as 75% shear area or 75%SA).

The factors which can be manipulated to

achieve a high level of strength while retaining sufficient intrinsic toughness to meet the Gas Council DWTT requirement of 75%SA at $0^{o}C$ are discussed below:

Irvine (1969) and Irvine et al (1967) using multiple regression analysis developed the following equations to describe the yield stress and ductile/brittle transition temperature in ferrite-pearlite steels:

Eq.1. Yield Stress (N/mm^2) = $69.5 + 32.4\%Mn + 83.4\%Si + 355.2(\%N_f^{1/2}) + 17.5d^{-1/2} + \Delta ptn$.

Eq.2. Ductile/brittle transition temperature, T_c (^{o}C) = $-19 + 44\%Si + 700(\%N_f^{1/2}) - 11.5\, d^{-1/2} + 2.2(\%$ pearlite$) + 0.26\, \Delta ptn$.

where N_f = the free nitrogen content

d = ferrite grain size, mm

Δptn = a precipitation strengthening factor, N/mm^2

Equations 1 and 2 distinguish the basic parameters which can be manipulated by the steel maker in the optimisation of properties. Clearly the aim is to maximise Equation 1 whilst maintaining Equation 2 at an acceptable low value. Unfortunately some of the factors which benefit Equation 1 have an undesirable, and in some cases unaccepatable, effect on Equation 2. These factors are discussed below in four sub-sections which emphasis the important manufacturing practices.

3.1 Melting Practice: The production of steel involves the removal of impurities from molten pig iron by a process of oxidation. On completing of this purification process the molten metal contains high levels of dissolved oxygen and nitrogen. The dissolved oxygen may be removed by the addition of silicon and manganese. It is then possible to make additions of aluminium which, in the absence of oxygen, eventually combine with the dissolved nitrogen to form aluminium nitride particles after the steel has solidified. Such material is known as a fully-killed, aluminium treated steel. It may be seen that the effect of adding aluminium is the reduction of the free nitrogen content (normally to levels of approximately 0.001% in fully killed steels). This has a particularly beneficial effect on Equation 2.

3.2 Grain Size Control: The purified molten steel is poured into moulds to produce ingots. These ingots are then mechanically worked by hot rolling to produce plates of the desired dimensions for pipe manufacture. It is during this hot working process or in subsequent heat treatment of the plate that the vital aspect of grain size control is introduced.

Reference in Equartions 1 and 2 indicates that reduction in grain size has the dual advantage of giving both high yield strengths and low transition temperatures. As a result, most modern steel processing routes rely mainly on grain size control to achieve high levels of strength and toughness. Two alternative approaches are possible, namely-

3.2.1 Controlled Rolling: Most steel plate is produced by rolling at temperatures above $1,000^{o}C$. At these high temperatures the steel is relatively soft and easy to deform. In the mid 1960›s the work of Duckworth and his associates at the British Iron and Steel Research Association showed that much finer grain sizes could, however, be obtained by continuing the rolling operation down to temperatures as low as $750^{o}C$ [Duckworth et al (1965)]. This practice became known as controlled rolling because the rolling schedule has to be controlled to optimize the properties obtained.

3.2.2 Normalising: The properties of plate produced by conventional rolling techniques can be improved by heat treatment at approximately $900^{o}C$. This causes the grain structure of the steel to recrystallise and if properly controlled can produce very appreciable reduction in grain size. Fully-killed steels have a particularly strong response to this treatment, largely because of the presence of small aluminium nitride particles. These particles lead to better grain size control by a complex multiple influence, which is beyond the scope of the present paper [Gladman (1967)]. The same effects can also be achieved by making micro-additions of niobium and /or vanadium. These elements react with both the carbon and nitrogen present to form small carbo-nitride particles.

3.3 Reduction of Pearlite Content: Raising carbon content of the steel increases the amount of pearlite present. Reference to equations (1) and (2) indicates that with increasing pearlite content the transition temperature (T_c) rises and the yield stress remains unchanged. The effect of addition of carbon is therefore detrimental.

3.4 **Precipitation Strengthening:** Reference has already been made to the possibility of adding small amounts of vanadium and/or niobium to the steel. The size of the carbon-nitride particles formed by these additions depends on the thermal history of the steel. In normalised steels many of the particles tend to be relatively coarse ($\sim 10^{-4}$ mm), and have little or no direct effect on strength, however, some of the particles can be much finer ($\sim 10^{-5}$ mm) and these interfere with the deformation processes that occur when the steel is subjected to a load. The effect of the fine precipitated particles is to raise the yield strength by an increment . Unfortunately T_c is also raised by a factor directly related to .

In summary, the achievement of a steel with a combination of high strength, good toughness, and good weldability requires the careful control and balancing of a number of sometimes opposing factors.

4. RESISTANCE TO DUCTILE FRACTURE PROPAGATION

In a previous section it was shown that pipeline steels must have adequarte levels of Charpy upper shelf energies to ensure freedom from propagating ductile fractures. Various microstructural features are known to affect the USE energy with two main factors being:

(a) Non-metallic inclusions
(b) Carbon content

The effect of carbon content on the Charpy impact transition curves is shown in Fig.5 and it is clear that increasing the carobon content produces large decreases in the USE valves. However, in linepipe steels the range of carbon contents is somewhat limited and so the effect of carbon is less importent.

The non-metallic inclusions which are present to some extent in all steels are believed to play the most important part in determining USE levels. By acting as planes of weakness the non-metallic inclusions nucleates voids ahead of an advancing ductile fracture, and thus reduce the energy required to cause the fracture. Consequently, the more inclusions present and the greater their deformation, the less resistance the steel will have to ductile fracture.

In pipeline steels the majority of inclusions are of the manganese sulphide type and these have been found to have a particularly detrimental effect on the ductile fracture resistance of pipeline steels. During the hot rolling of the steel plate, these inclusions deform into extremely long, thin elliptical plates, with the major axis of each ellipse parallel to the rolling direction. The ellipsoidal shape of the inclusions produces a directional effect when measuring USE values. Figure 6 shows that Charpy specimens taken in the longitudinal direction have significantly higher USE values than specimens taken in the transverse direction.

The shape of inclusions can be modified by a number of methods, one of most effective being the addition of rare earth metals (REM) to the steels [Luyckx et al (1970) and Browning et al (1970)]. The REM sulphides are thermodynamically highly stable compounds and form in preference to manganese sulphide. Furthermore, they are relatively hard and non-plastic, so that their shape is affected far less by the hot working of the steel plate. This change is inclusion morphology has a highly beneficial effect on USE values (as shown in Figure 7), with the transverse USE values increasing almost to the level of longitudinal specimens. More recently calcium additions have been found to have the same effect as rare earth metals in producing almost spherical inclusions.

A different approach to the problem became available with the development of cross rolling techniques. These involve hot rolling of the steel first in one direction and then at right angles to this direction. This removes the disparity between the longitudinal and transverse dimensions of MnS inclusions and substantial improvements in transverse USE values have been achieved by the application of cross rolling in the production of pipeline steels.

The application of one (or more) of these methods for inclusion shape control produces USE levels of acceptable magnitude.

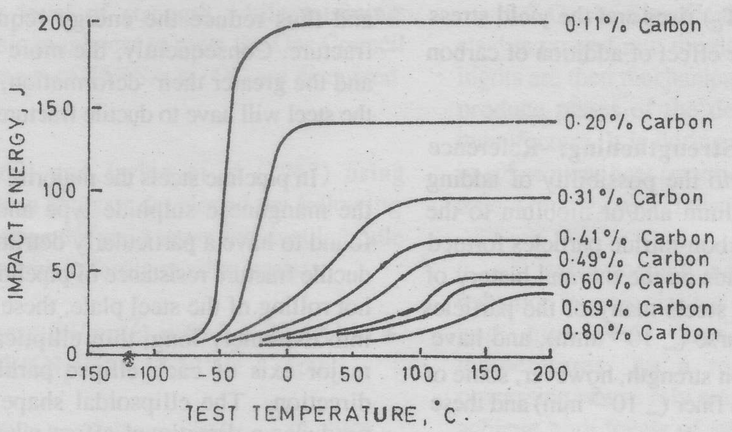

Figure 5 Effect of carbon content on the Charpy USE

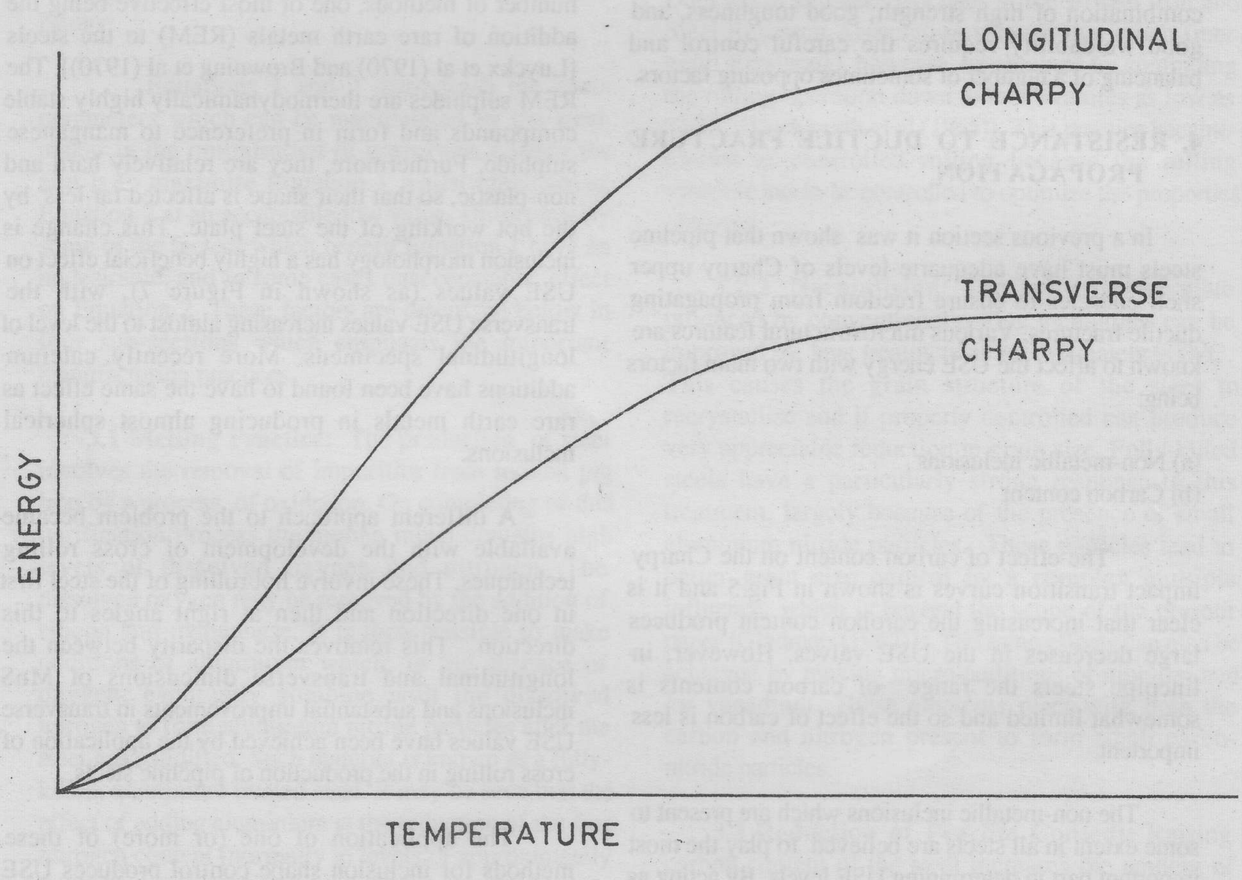

Figure 6 Effect of Charpy specimen orientation of USE levels

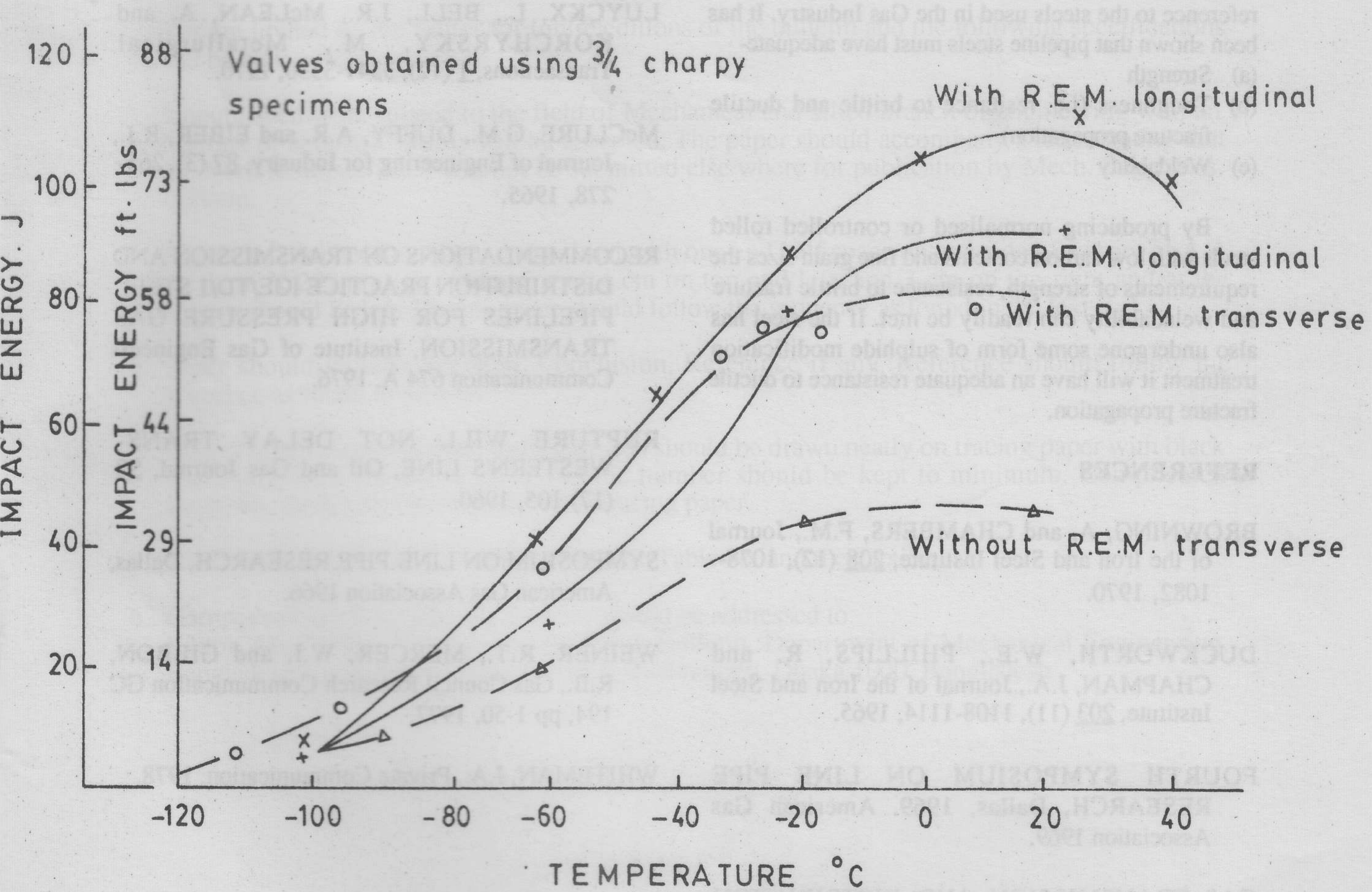

Fig. 7. Effect of R E M addition on charpy USE levels

5. SUMMARY

This paper has briefly summarised some of the major developments in HSLA steels, with particular reference to the steels used in the Gas Industry. It has been shown that pipeline steels must have adequate-

(a) Strength
(b) Toughness (i.e. resitance to brittle and ductile fracture propagation)
(c) Weldability

By producing normalised or controlled rolled steels with low carbon contents and fine grain sizes the requirements of strength, resistance to brittle fracture and weladability can readily be met. If the steel has also undergone some form of sulphide modification treatment it will have an adequate resistance to ductile fracture propagation.

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