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On the Embrittlement and Toughness of High Purity Fe–30Cr–2Mo Alloy*

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Synopsis

Experiments were conducted to explain unexpected embrittlement phenomena encountered in fabricating a high purity Fe–30Cr–2Mo alloy. By means of a hydrostatic tensile test with a Bridgman-Type specimen it was found that the fracture behaviour of the alloy is highly dependent on stress state. Under conditions of low triaxial stress, the alloy displays excellent ductility. Under conditions of high triaxial stress, however, the alloy shows less strain to fracture and a transition from ductile to cleavage fracture. The toughness of the Fe–30Cr–2Mo alloy can be significantly improved by thermomechanical processing.

I. Introduction

The Fe–30Cr–2Mo alloy is a high purity stainless steel produced by vacuum induction melting with relatively pure raw materials. Deoxidation using both aluminium and calcium is required in the melting to get low oxygen content and to suppress interstitial impurities, carbon plus nitrogen, to below 120 ppm. Further a duplex process combining an electric furance with vacuum oxygen decarburization (VOD) practice, i.e., so-called "strong stirring VOD" process(1), has been established commercially to produce high purity Fe–26Cr–1Mo and Fe–30Cr–2Mo alloys. The Fe–30Cr–2Mo alloy has superior resistance to stress corrosion cracking and to pitting and crevice corrosion in chloride-containing environments(2,3). The alloy becomes more and more available as a new material for chemical process industry. For example, a rectifying tower in an acetic acid plant which is made of 6 mm thick plate of the Fe–30Cr–2Mo alloy has now been satisfactorily in service. Important problems still to be unsolved are to improve toughness, as-welded ductility and formability of thicker sheet. The object of the present work is to study the embrittlement phenomena in deformation processing, the effect of

* The **1698th** report of the Research Institute for Iron, Steel and Other Metals.

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(1) S. Iwaoka, H. Kaito, T. Ohtani, N. Ohashi, M. Takeda and N. Kinoshita, Stainless Steel '77 a global forum Climax Molybdenum Co. (1977).

(2) T. Morimura, Kinzoku, **42**(1972), 130.

(3) S. Shimodaria, H. Saito, T. Morimura and T. Hirano, Presented at Japan Society of Corrosion Engineering, May 12–14, 1976.

thermomechanical treatment on the toughness, and the fracture behavior in the multiaxial state of stress.

II. Unexpected embrittlement phenomena encountered during deformation processing

The ductility of the alloy is very high in unidirectional mechanical testing(4). It has also been found to be readily fabricated and easily cold-formed into shapes. For example, the hot rolled plate of 6 mm thick can be rolled at room temperature to foil of 0.006 mm thickness without intermediate annealing. However, the early research and development of the commerically made alloy was suffering from unexpected embrittlement phenomena during the deformation processing. Some exmaples are as follows.

Example 1. Hair cracks in forged billet

A 500kg ingot (260 mm dia. and 600 mm height) was forged to billet of 35 mm thick in the temperature range from 750°C to 1000°C and cooled in air. Hair racks were found in the cross section of the billet by dye check. Micromechanism of the hair crack formation was cleavage fracture. The cause seemed to be interaction between residual stress in the billet and 475°C embrittlement induced during the cooling process.

Example 2. Ring-shaped failure during pipe drawing

A pipe, extruded at 1000°C with glass lubricant and water quenched, was drawn at room temperature without plug from a 43 mm outer diameter to 40 mm. Ring-shaped circumferential cracks were found on the surface of the pipe. The micromechanism of failure in this case also was cleavage fracture.

Example 3. Penny-shaped central bursting during rod drawing(5)

When the rod annealed at 1000°C and water quenched was drawn from 26.5 mm dia. to 23.0 mm dia. at room temperature, the periodic development of internal flaws were detected by means of γ-ray. The internal flaws were different in shape and fracture mechanism from the usual type of central bursting during conventional rod drawing. The shape was not chevron but penny-shaped and also the micromechanism was not ductile (or dimple) fracture but cleavage fracture. Moreover, a number of deformation twins were observed in the vicinity of the flaws. The conclusions obtained by analysis(5) are: (i) the flaw is formed by cleavage fracture at the centerline of the billet, depending on the stress state during drawing, (ii) in a drawing the hydrostatic stress components are mostly tensile according to slipline field analysis, and the damage by a critical tensile stress is most severe along the centerline despite the small amount of deformation and strain-hardening involved in the drawing, and (iii) the flaw

(4) K. Ichikawa, Kinzoku Zairyo, **17** (1977), No. 6, p. 33.
(5) M. Shimura, Trans. Jpn. Inst. Met., **19** (1978), 589.

grows in a direction perpendicular to the highest tesnile stress in a discontinuous cleavage manner to form the penny shape.

Example 4. Internal cracking during rolling of thick plate

When a thick plate (thickness 32 mm) annealed at 1000°C and water quenched was rolled at room temperature to a thickness of 26 mm in 3 passes, the formation of cavity-like flaws was found in the central part of the plate. They were periodic in the direction of rolling and were connected partially each other to form so-called "crocodiling" – like cracking. Also in this case, the fracture mechanism of cracking was mainly cleavage in the direction perpendicular to the plate surface, and numerous deformation twins were observed in the vicinity of the cracks. This case is an example in which crackings were found during rolling. There is, however, another case in which the crackings were not found during rolling but were found later on the fracture surface of a Charpy impact specimen taken from the plate.

The investigation of cracking behaviour in each case described above was conducted at fabricating plants in full detail. These troubles in fabrication of the alloy were overcome technically by the improvements in fabricating conditions, viz. cooling rate, composition, distribution of carbides, heat treatment and deformation schedule, etc. The common features of crackings in the above mentioned cases are as follows:

(i) Fracture occurred under the complex state of stress.
(ii) Micromechanism of fracture was cleavage fracture.
(iii) Numerous deformation twins were observed in the vicinity of the cracks.
(iv) Fracture occurred at relatively small amount of deformation.
(v) Fracture occurred with quite coarse grained structure.

It is suggested that the five features seemed to be closely connected with the workability ot the alloy in the bulk deformation process and with ductile-brittle transition phenomena in the alloy.

III. Fracture behaviour under the state of hydrostatic tensile stress as a measure of the workability and toughness

In describing the failure of metals in forming operations, it is necessary to consider both the operative state of stress and the mechanism of failure in relation to the microstructure. Several criteria of the internal fracture are based on the effect of hydrostatic pressure in suppression of ductile fracture and of tensile stresses in promoting fracture(6). To date, however, little data are available on this aspect, although some valuable progress has been made in the discussion of the influence of hydrostatic pressure on the strain to failure resulting from void nucleation and growth(7,8). It is also reported that cleavage fracture is more

(6) H.C. Rogers, *Metal Forming – Interrelation between Theory and Practice,* The Met. Soc. AIME Proceeding (1971), 453.
(7) J.R. Rice and D.M. Tracey, J. Mech. Phys. Solids, **17** (1969), 201.
(8) L.M. Brown, *The Mechanics and Physics of Fracture,* Metal Society, London (1976).

influenced by pressure at the stage of grain boundary crossing(9). Therefore, experimental studies of the influence of negative pressure (hydrostatic tension) on microscopic processes of fracture were carried out with Fe–30Cr–2Mo alloy.

Experimental procedure

A heat of the alloy of 1 ton in weight was produced by a process of vacuum induction melting using high purity charge materials. The ingot was forged to slabs of 35 mm thick and 110 mm wide. The chemical composition is given in Table 1. Bridgman type specimens machined from the slabs were used in order to investigate the effect of hydrostatic tension on fracture behaviour of the alloy. In his pioneering study(10) on the effect of pressure on fracture, Bridgman obtained an approximately solution for the distribution of stress and plastic strain across the plane of the neck at the narrowest cross-section, for a given longitudinal profile radius of curvature on the neck in a round bar. The stress distribution is shown in Figure 1. Direct comparison of the extension of the Bridgman analysis for the distribution of negative pressure with the results of recent numerical computation(11) demonstrate that this solution is rather good near the neck. Therefore, the necked region of a bar with its distribution of plastic strains and negative pressure along the axis is a convenient plastic flow field for experimental studies of fracture behaviour of the alloy. In round bar with initially machined grooves, however, the axial plastic strain increments may be no longer be uniform along the plane of the neck, as is necessary for Bridgman solution, making that solution no longer valid(12). The departure from a condition of uniaxial strain in bars with initially machined longitudinal profile is a result of a departure of the machined profile from the natural neck geometry.

So, in the first stage of the experiment, a number of natural profiles of necks were carefully measured on a steel bar. From such measurement it was determined that the natural neck profile can be described to a high degree of accuracy by the empirical equation developed by Dondik(13). Then, Bridgman type specimens with

Table 1. Chemical composition of test material

C	Si	Mn	P	S	Ni	Cr	Mo	Al	O	N	Nb
0.002	0.14	0.05	0.02	0.01	0.17	30.3	1.9	0.11	0.002	0.006	0.10

(9) D. Francois, "The influence of hydrostatic pressure on fracture", Proceeding ICF 4, (1977), vol. 1, p. 805.
(10) P.W. Bridgman, *Studies in Large Plastic Flow and Fracture*, New York, McGraw-Hill (1952), 9.
(11) A. Needleman, J. Mech. Phys. Solids, **20** (1972), 111.
W.H. Chen, Int. J. Solids Structures, **7** (1971), 685.
D.M. Norris *et. al.*, J. Mech. Phys. Solids, **26** (1978), 1.
(12) D.P. Clausing, J. Mater., **4** (1969), 566.
(13) I.G. Dondik, Problemy Prochnosti (1970), No. 8, p. 54; Strength Mater. (1972), 937.

the natural necking profile after the Dondik's equation were machined using a numerically controlled lathe, as shown in Figure 2.

The diameter of the narrowest portion of the neck of the specimen was 16 mm, and the minimum longitudinal radius of curvature at the neck was 3 mm~45 mm. The grain size of this material after annealing at 1000°C was ~500 μm. Tensile tests were carried out at room temperature.

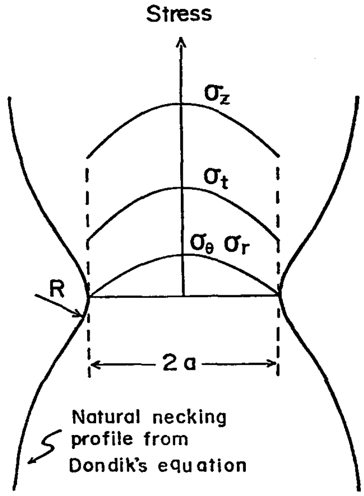

Fig. 1.

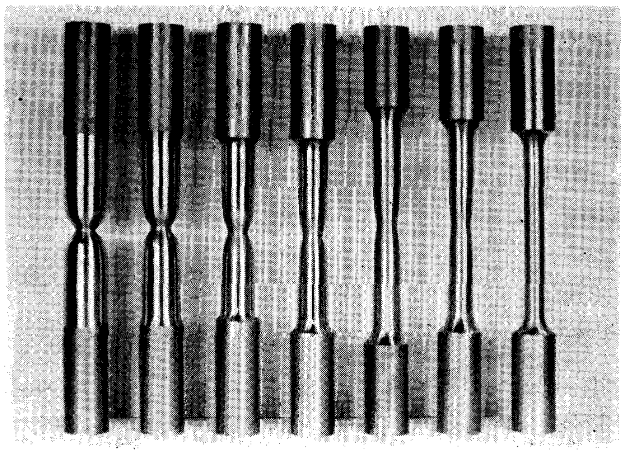

Fig. 2.

Fig. 1. Illustration of the Bridgman type specimen with natural necking profile and distribution of longitudinal stress component, σ_z, hydrostatic tensile stress (negative pressure) component, σ_t, radial stress component, σ_r, and circumferential stress component, σ_θ, at the narrowest cross-section. R is the minimum longitudinal (profile) radius of curvature at the neck and, a is the radius of the narrowest portion of the neck.

Fig. 2. Bridgman type specimens with the natural necking profile machined with numerical controlled lathe.

Results

Figure 3 shows the results of the tensile tests. The ordinate represents reducrion of area, and the abscissa represents the mean value of maximum hydrostatic tensile component in the deformation process. The subscale refers to maximum tensile stress. As seen in this figure, the higher the hydrostatic tensile stress, the lower the fracture strain. The results of the same experiments with 0.45%C steel and 0.25%C steel are also shown in the figure for comparison. The influence of the hydrostatic tension on the fracture behaviour of the alloy is higher than those of these carbon steels. While the fracture strain is very large in low triaxiality, the fracture strain decreases abruptly, as the value of hydrostatic tensile component increases. Moreover, the results of the specimen aged for 1 hour at 475°C and of the specimen prestrained are shown in the figure for comparison.

The figure shows also the fracture modes. In the figure, the code, open cricle, denotes overall fibrous fracture. The code, double cricle, denotes bimodal fracture, which contains fibrous region in the middle parts of the fracture surface and cleavage fracture around the fibrous region. The crossed circle denotes overall cleavage fracture. It is noticeable that two types of transition from ductile to cleavage are involved in the process of fracture. The one is the production of cleavage fracture as a function of negative pressure and the other is fibrous-cleavage transition in the growth of the crack. The fracture surface in the high hydrostatic tensile state consists mostly of cleavage surface, while it is fibrous in the stress state of low triaxiality. It is suggested that a ductile-brittle transition pressure DBTP (negative), may exist from the analogy of ductile-brittle transition temperature, DBTT. The fracture surface shows bimodal fracture in the range of transition pressure. In this range, fibrous fracture initiates in the central part of the neck and propagates radially, as shown in Figure 4. Figure 5 shows the transition phenomena from fibrous to cleavage failure as the crack grows.

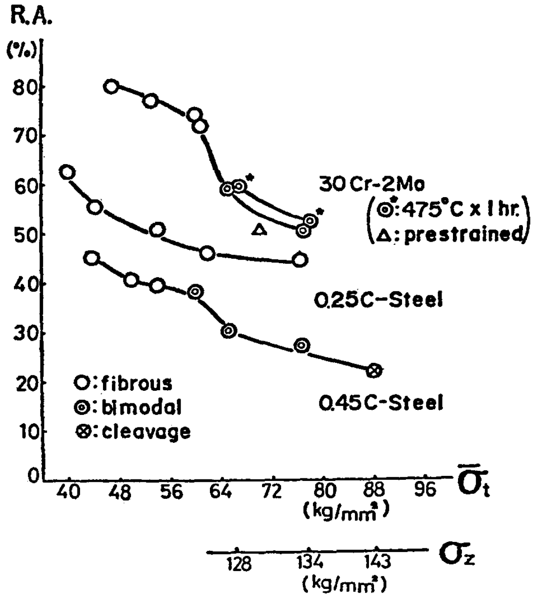

Fig. 3.

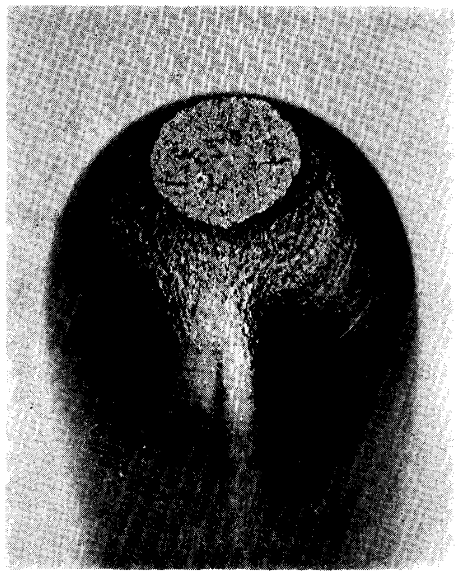

Fig. 4.

Fig. 3. Influence of hydrostatic tensile stress on the fracture behaviour of Fe–30Cr–2Mo alloy. The ordinate denotes reduction of area (or strain to fracture) and the abscissa denotes the mean value of maximum hydrostatic tensile component, σ_t, then the subscale denotes the value of maximum tensile stress component, σ_z.

Fig. 4. Light Fractograph: Fracture surface of the Bridgman type specimen (radius of narrowest porition of the neck is of 8 mm and minimum longitudinal radius of curvature at the neck is of 4.5 mm) of Fe–30Cr–2Mo alloy. It shows the typical bimodal fracture.

IV. Thermomechanical processing for improvement of impact property

Several factors control the impact property of ferritic structural steels. The most important one among these is grain size, since the decrease in grain size can

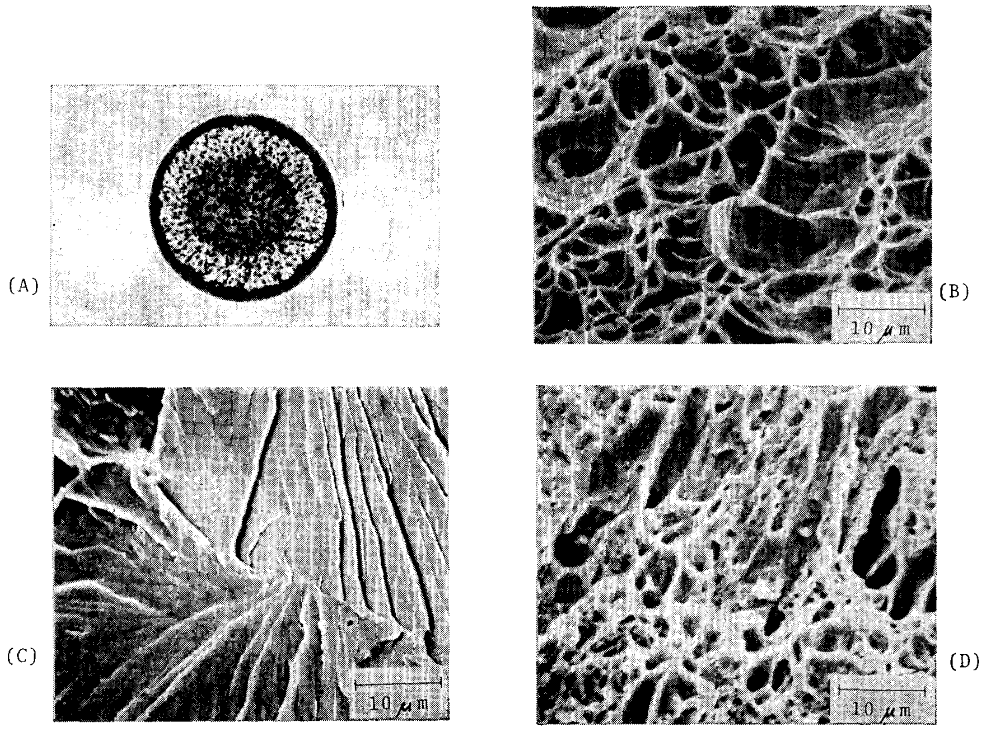

Fig. 5. Light Fractograph and SEM Fractographs: Fe–30Cr–2Mo alloy, fractured by hydrostatic tension at room temperature. Typical bimodal fracture. X4. (A) L.F. Fracture started at the center of the fibrous zone. The outer ring is the cleavage zone and the circumferential narrow zone is the shear-lip zone. (B) SEM F. Dimple fracture mode in the central, fibrous zone. (C) SEM F. Cleavage fracture mode in the outer zone. (D) SEM F. Shear mode dimple fracture in the circumferential zone.

raise both yield stress and notch ductility. It has been pointed out that uniform recrystallization is a prerequisite for stable isotropic impact property of steel products – the finer the grain size, the higher the energy absorbed(14). According to the data presented by Franson(15), however, hot worked structure in high purity Fe–26Cr–1Mo alloy is more resistant to recrystallization than cold worked structure, so that annealing temperatures of 1600°F or higher are required to get full recrystallization of the hot-worked structure. The resultant grain size is therefore quite large. The Fe–30Cr–2Mo alloy also needs a high annealing temperatures, with in attendant coarse-grained structure and hence low impact properties. The DBTT of thick plate is easily affected by high temperature annealing coupled with a slow cooling rate after hot–working. Currently, two methods are applied for grain refining, i.e., controlled rolling and heat treatment. Controlled rolling offers a good scope for strong grain refining, not only because it is possible to set down rolling schedules to produce varying degree of grain refinement, but also because the controlled rolling procedures are

(14) W.A. Matejka and R.J. Knoth, ASTM Symposium New Higher Cr Ferritic Stainless Steels, Bal Harbour, Florida, Dec. 6, 1973.
(15) I.A. Franson, Metall. Trans., **5** (1974), 2257.

applicable to virtually all alloy combinations[16]. In general, the process for low alloy carbon steels involves good control of the deformation schedule and temperature, especially during the final stage of rolling. And, the greater the reduction and the lower the temperature in the last pass, and the shorter the time taken for complete recrystallization, the finer the grain size. Post rolling normalizing treatments are frequently given in order to improve the properties of rolled plate. The principles of recrystallization and inhibitation of grain growth may be used in both the ferritic and austenitic conditions.

Experimental procedure

Several laboratory rolling experiments were conducted to examine the effect of different types of reduction schedule and of post rolling heat treatments on ferrite grain size and on impact properties in the Fe–30Cr–2Mo alloy. Figure 6 shows the processes, schematically. The initial flat thickness was 35 mm and the final thickness was 7 mm. Individual processing steps are as follows:

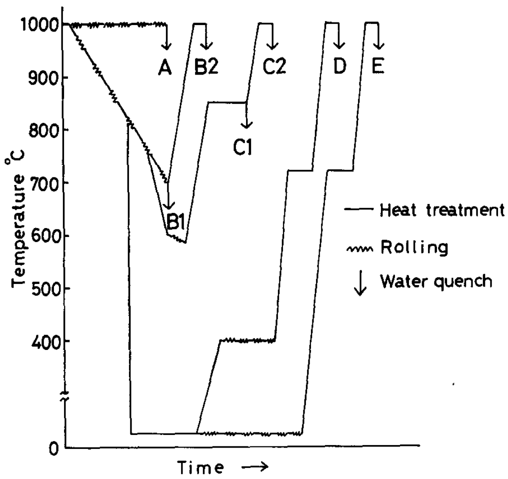

Fig. 6. Schematic illustration of the thermomechanical processing.

A. One heat one pass at 1000°C. Constant 5 mm thickness draft per pass. Annealing at 1000°C for 5 min. and water quenching.

B. Conventional, continuous rolling. Constant 5 mm thickness draft per pass. The finishing temperature was about 700°C.

B.1 Annealing at 1000°C for 5 min. and water quenching.

B.2 Annealing at 850°C for 10 min. water quench, subsequent annealing at 1000°C for 5 min. and water quenching.

C. Thermomechanical processing (TMP). Constant 5 mm thickness draft per pass up to 12 mm thick, and then 5 mm thickness draft in the last pass. The finishing temperature was approximately 600°C.

(16) T.G. George, G. Bashford and J.M. MacDonald, J. Aust. Inst. Met., **16** (1961), 36.

C.1 Annealing at 850°C for 20 min. and water quenching.

C.2 Annealing at 850°C for 20 min. water quench, subsequent annealing at 1000°C for 5 min. and water quenching.

The second set of experiments was conducted to examine the effect of the combination of warm rolling or cold rolling and the post rolling heat treatment.

D. Constant 5 mm thickness draft per pass to 16 mm thick, with a finishing temperature of approximately 800°C, followed by subsequent four passes with constant reduction to 7 mm thick at 400°C.

E. Constant 5 mm thickness draft per pass to 16 mm thick, and with a finishing temperature of approximately 800°C, followed by six passes with constant reduction to 7 mm thick at room temperature. Annealing at 720°C for 10 min. water quench, annealing at 1000°C for 5 min, and water quenching.

The prior heat treatment in the post rolling was for activating simultaneously a large fraction of the potential nuclei for recrystallization, and the subsequent heat treatment was for softening.

Charpy impact specimens of 6 mm thick were cut in parallel to the rolling direction from the rolled plate.

Results

Table 2 shows the conditions of the process and the results of ferritic grain size determinations. A comparison of the results show that there is a tendency towards fine grain sizes for schedules involving both the working of lower temperature at the last pass and the heat treatment for activating the nuclei for recrystallization.

Table 2. Effect of processing condition on ferrite grain-size

Processing	Temperature °C			ASTM Grain size	Hardness Hv
	Finishing	1st anneal	2nd anneal		
A	1000		1000	1-2	208
B1	700		1000	3-7	203
B2	700	850	1000	3-7	210
C1	620	850		8-9	208
C2	620	850	1000	7-6	212
D	400	720	1000	8	208
E	20	720	1000	8	232

The conventional hot rolling of the alloys results in a pancake structure of grain highly elongated in the rolling direction and in a moderately strong cube-on-edge texture. The elongated-grain boundaries and textures form more or less continuous easy fracture paths in the plane normal to the short transverse direction. Figure 7 shows the fracture surface of the specimen taken from the conventionally, continuously hot rolled materials, impact fractured at –30°C. The fracture

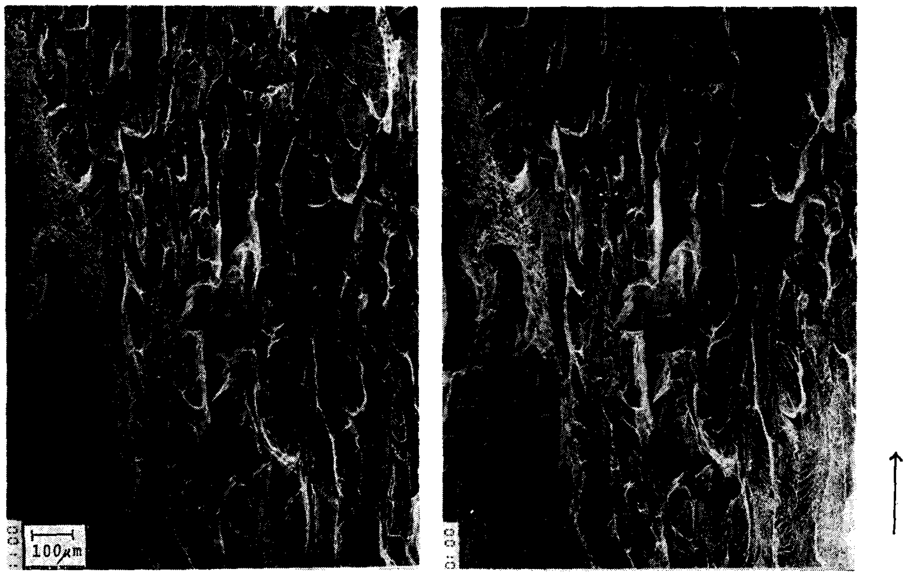

Fig. 7. SEM Stereofractograph: Fe–30Cr–2Mo alloy, conventionally, continuously hot-rolled, fractured by Charpy impact at –30°C. Arrow shows the rolling direction.

surface shows a brittle mode consisting cleavage fracture and so-called delamination along the rolling direction. The upper–shelf energy level was low and the ductile-brittle transition temperature was high in the case. The annealing of the conventionally, hot-rolled structure at 1000°C brings about very large grain size. The fracture mode of the charpy impact specimens of the material annealed at 1000°C was discontinuous propagation of cleavage at the lower shelf energy level. However, the characteristics appeared in the hydrostatic tensile test have been observed on the fracture surface. A narrow irregular network was observed at the grain boundaries on the cleavage fracture surface, as shown in Figure 8. Figure 9 shows the enlarged state of grain boundary.

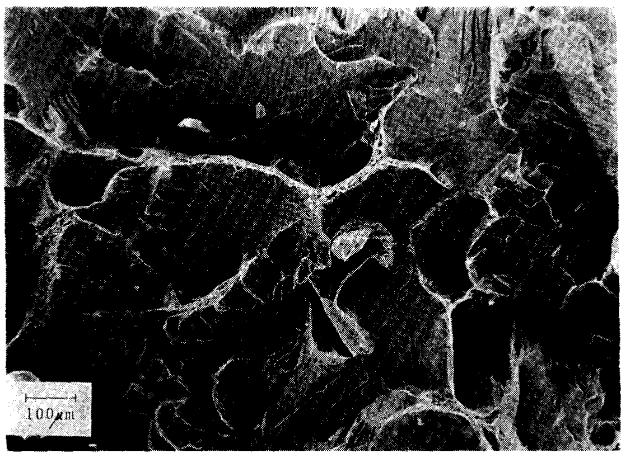

Fig. 8. SEM Fractograph: Network of dimple strips on the cleavage fracture surface. Fe –30Cr–2Mo alloy, conventionally, continuously hot-rolled and annealed at 1000°C, fractured by Charpy impact at 0°C.

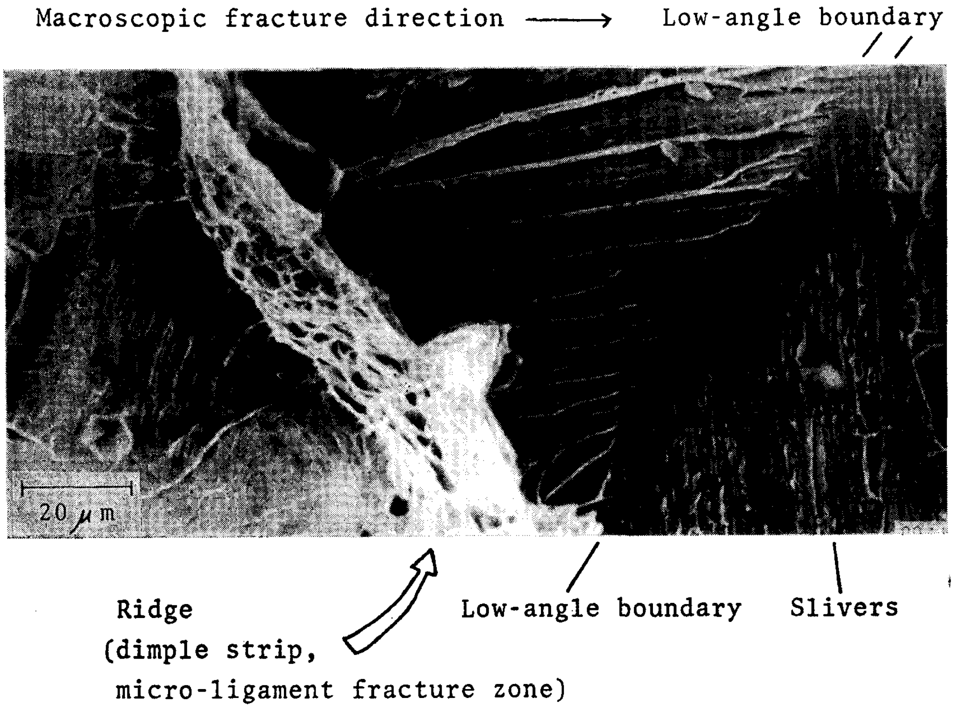

Fig. 9. SEM Fractograph: Dimple strip formed by micro-ligament fracture in the vicinity of grain boundary on the cleavage fracture surface. Fe–30Cr–2Mo alloy, conventionally, continuously hot-rolled and annealed at 1000°C, fractured by Charpy impact at 0°C.

It seems probable that this network, containing very fine, equiaxed dimples, was developed in the process of micro-ligament fracture under the local, unidirectional tensile state in the vicinity of the grain boundary[17]. The impact energy absorbed by the conventionally hotrolled materials and by the subsequently annealed materials are shown in Figure 10. The levels of absorbed energy are low and the ductile-brittle temperature are near the room temperature, in both cases. Figure 11 shows the impact energy absorbed in the materials made by the TMP of C. The results show that an adequate combination of pass schedule and post rolling normalizing has a pronounced effect on the impact properties. The influence of the TMP on form and position of the impact transition curve is very marked. In a TM treated plate, brittle fracture begins at a much lower temperature. The impact transition curve, however, shows a gradual decrease in a wide temperature range between brittle fracture and upper sehlf. The controlled rolled high strength low alloy (HSLA) plate shows a pronounced tendency to splitting of the fracture planes. The cause of this splitting seems to be a weakening of the previously elongated grain boundaries due to precipitation[18]. In the case of the TM treated Fe–30Cr–2Mo alloy, the influence of the previous grain boundaries, which are parallel to the plate surface, was recognized on the fracture surface, although a

(17) M. Shimura and H. Tokuno, Trans. Jpn. Inst. Met., to be published.
(18) L. Meyer and H. de Boer, J. Metals, (1977), Jan., p. 17.

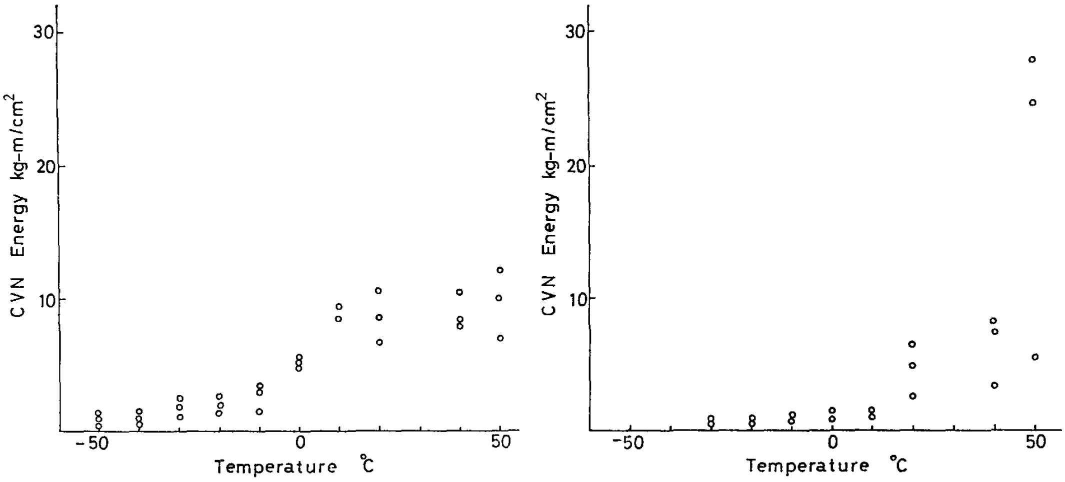

Fig. 10. Effect of conventional processing on the impact resistance of 6 mm thick Charpy V-notch samples B–1 and B–2.

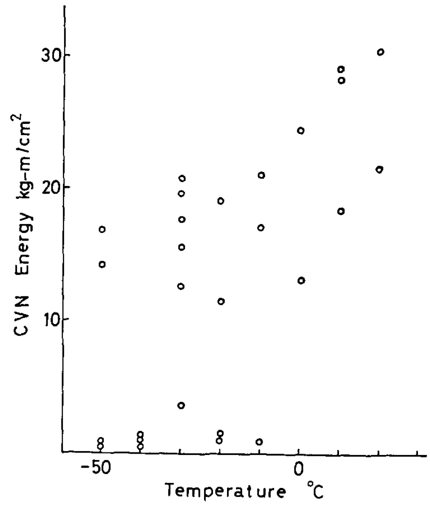

Fig. 11. Effect of thermomechanical processing on the impact resistance of 6 mm thick Charpy V-notch sample C–1.

pronounced tednency to splitting could not be observed, as shown in Figure 12. Good results were obtained in process D and E, as shown in Figure 13. These processes are placing mill restrictions, however, because of too high loading.

V. Discussion

Fracture behaviour in hydrostatic tensile state

The results of hydrostatic tensile test with the Bridgman-type specimens of coarse-grained structure show that the fracture behavior of Fe–30Cr–2Mo alloy is more strongly dependent on the value of the hydrostatic tensile stress component than the plain carbon steel. While the fracture strain is very large in low

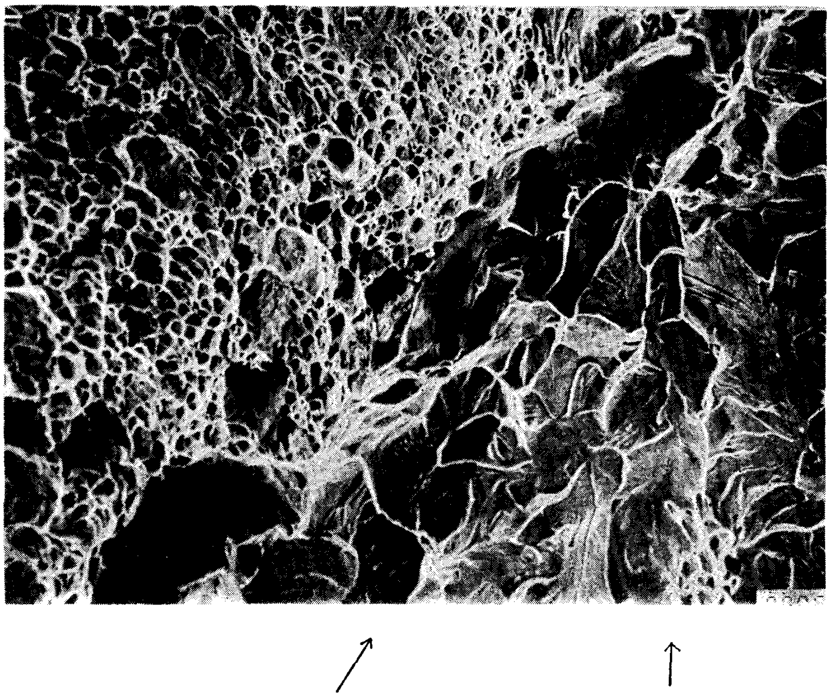

Fig. 12. SEM Fractograph: Fe–30Cr–2Mo alloy, thermomechanically processed, fract red by Charpy impact at –50°C. Arrows show previous grain boundaries. Scale mark shows 100μm.

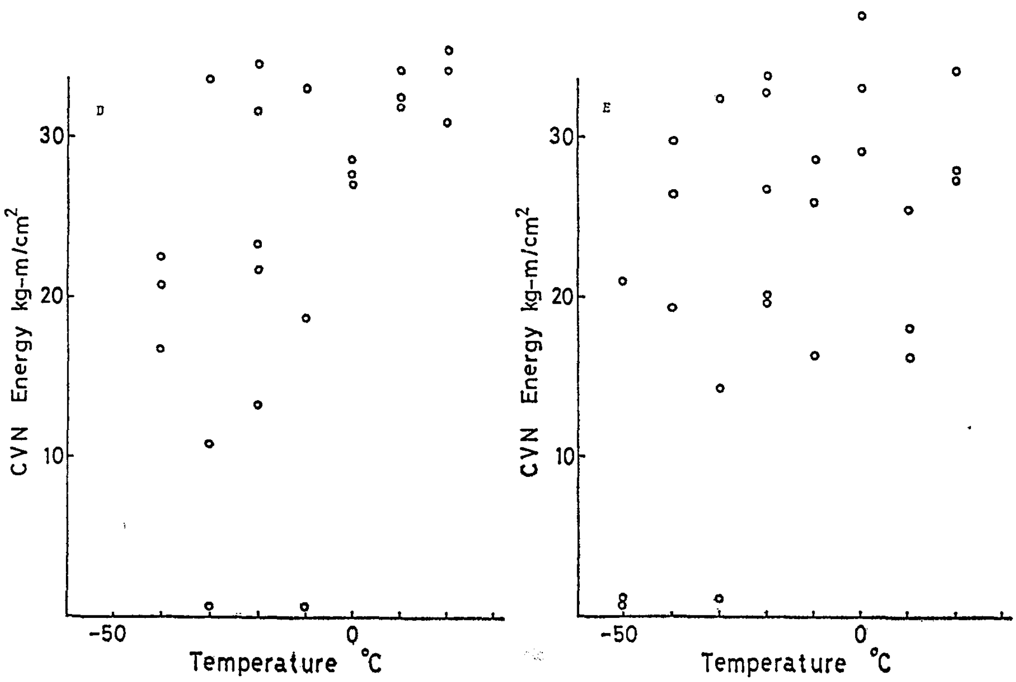

Fig. 13. Effect of thermomechanical processing on the impact resistance of 6 mm thick Charpy V-notch samples D and E.

triaxiality, it decreases abruptly as the value of hydrostatic tensile component increases. Under conditions of low triaxial stresses, the alloy displays excellent ductility. Under conditions of high triaxial stresses, however, the alloy shows less strain to fracture and a transition from ductile to cleavage fracture.

One of the principal aims of the investigation was to determine whether a "damage sensitivity" parameter could be assigned to the various materials studied, which would indicate their propensity to the generation of damage, when deformed under equivalent processing conditions. The unexpected embrittlement phenomena, as mentioned previously, can be well explained qualitatively by the experimental results. The results suggest that to the left of the double circle points in Figure 3, the state of stress are considered to be favorable for processing. The Cockcroft criterion(19) for workability, which suggests that fracture will occur when the tensile strain energy reaches a critical value, was applied with a high degree of success only in the range of fibrous fracture, but not in the case of bimodal fracture. There was, however, a discrepancy between the values of hydrostatic component or maximum tensile stress component for cleavage fracture from the testing and the values estimated by the applciation of slip-line field theory on the deformation processing(5).

The cause of the discrepancy is not clear from the results of the experiment but it can be considered that there are many problems remaining unsolved, for example, strain dependency or history dependency of cleavage stress in the alloy, and/or slip-initiated cleavage and twin-initiated cleavage in the alloy. Moreover, based on limited data, the specimen aged at 475°C for 1 hour displayed a fracture strain equal to the unaged a pecimens and there is no difference in the fracture surface. The specimen, prestrained at room temperature, displayed some resistance against to for the bimodal fracture.

The two fracture mode, dimple and cleavage fracture appearing in the hydrostatic tensile test, are expected to be influenced strongly by the microstructure. Consequently, if the hydrostatic tensile testing is to be applied to the thermomechanically treated materials, the results will be rather interesting.

Thermomechanical processing

The microstructure and the impact property are closely related. The finer the grain size, the larger the impact absorbed energy. However, the structure of the alloy after usual hotworking are quite coarse(15), and this influences the impact property, and especially the DBTT of the thick plate. The experimental results on the thermomechanical processing for improvement of the impact properties showed that the fine-grained structure (~ASTM No. 9) can be obtained and consequently the impact property can be improved substantially.

Metallurgically, the thermomechanical processing is connected with the

(19) M.G. Cockcroft and D.J. Latham, J. Inst. Met., **96** (1963), 33.

effect of the micro-alloying elements. A special characteristics of the micro-alloying element, columbium, during the thermomechanical processing, is the marked retardation of recrystallization, which leads to intense grain refinement.

There is a need to consolidate our knowledge on the effects of hot working with particular reference to the influence of derormation and temperature on recrystallization. In conclusion, the thermomechanical processing is regarded as a viable method for producing fine-grained structural and very tough materials, although it is somewhat disadvantages, economically and technically.

Deformation twinning

Generally, in cases where twinning is the operative mode of plastic deformation, twins may act as potent stress concentrators in the nucleation of cracks. In this case, when the traxiality is low and tensile stress at the onset of twinning is insufficient to propagate the nuclei, it may be raised by increasing the size of plastic zone beneath a notch (or internal defect) and hence the applied load on the specimen(20). While, when the triaxiality is high, the tensile stress below the notch as the twins are formed, is more than sufficient immediately to propagate any cracks nucleated by the "burst" of twins and final fracture is coincident with the onset of twinning(20). It is said that even coarse-grained mild steel, twin-initiated fracture would not be anticipated at temperature about 150°K, if the applied loading rate were equivalent to those normally obtained in standard fracture toughness testing(20). In coarse-grained Fe–30Cr–2Mo alloy, however, twin-initiated fracture may be able to occur at room temperature, and twinning may be easily associated with propagating cracks, because very high strain rates are produced ahead of the accelerating crack tip. Twinning usually takes place in materials containing few mobile dislocation soruces. Small amounts of prestrain at higher temperatures may therefore be effective to prevent twinning in the alloy. Grain-refining is, of coruse, most effective to prevent twinning.

Summary

The Fe–30Cr–2Mo alloy displays excellent ductility in conventional mechanical testing. Several unexpected embrittlement phenomena were observed in several deformation processings when the alloy had a coarse-grained structure and when it was in a complex state of stress. Experiments were conducted to explain the unexpected embrittlement phenomena by means of a hydrostatic tesnile test and to examine the effects of thermomechanical processing on the impact properties of the alloy.

The results of the tensile test of the coarse-grained materials in the hydrostatic tensile state shows that the fracture behavior of the alloy is highly dependent on the state of the stress. Under conditions of low triaxial stress, the alloy

(20) J.F. Knott, *Fundamentals of Fracture Mechanics*, Butterworths (1973), 198.

displays excellent ductility. Under conditions of high triaxial stress, however, it shows less strain to fracture and a transition from ductile to cleavage fracture.

Certain hot working and annealing conditions are effective in improving the impact properties of the alloy.

The successful use of high purity higher chromium ferritic stainless steel requires extensive understanding of the fracture characteristics of the alloy. Special attention should be paid to the conditions of deformation processing of the alloy with coarse-grained structure and the conditions of practical use of the thick plate. Producing of fine-grained structure is a most effective means of preventing the occurrence of the embrittlement.

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