| | |
|---|---|
| Title | Varestraint Test for Hot Crack Susceptibility of Chromium-Molybdenum Low Alloy Steels |
| Author(s) | Matsuda, Fukuhisa; Nakamura, Harumasa; Fujimaki, Hiroaki et al. |
| Citation | Transactions of JWRI. 1977, 6(2), p. 213-218 |
| Version Type | VoR |
| URL | https://doi.org/10.18910/9817 |
| rights | |
| Note | |

# Varestraint Test for Hot Crack Susceptibility of Chromium-Molybdenum Low Alloy Steels†

Fukuhisa MATSUDA*, Harumasa NAKAMURA**, Hiroaki FUJIMAKI** and Seiya SARUWATARI**

**Abstract**

*The Trans-Varestraint Cracking test was done with 1.25Cr-0.5Mo, 2.25Cr-1Mo, 3Cr-1Mo and 5Cr-0.5Mo low alloy steels whose carbon was varied from 0.05 to 0.2% and impurities as sulphur and phosphor were less than 0.01%. As a result, the susceptibility to the solidification cracking was increased with an increase of chromium alloying element and a decrease of carbon content. Therefore, it is predicted that special attention for the solidification cracking should be paid for the welding of low carbon 5Cr-0.5Mo and 3Cr-1Mo steels.*

## 1. Introduction

Chromium-molybdenum low alloy steels of 1 to 5 per cent Cr and 0.5 to 1 per cent Mo have been widely used in the manufacture of components of vessels and pipes for high temperature and high pressure services. Due to their high hardenability of base metal during welding, the careful precaution has been concentrated to the occurrence of the cold cracking in the HAZ and weld metal. Therefore, most reports concerning weld cracking of these steels have been treated for hydrogen contents in the weld metal, hardenability of the HAZ and restraint of the welded joints in relation to cold cracking problems. However, Wilkinson et al[1] have reported the occurrence of the hot cracking in the weld of 1 per cent chromium-molybdenum steel by argon-arc welding. They indicated the following results, (1) the major cause of hot cracking is attributed to sulphur, and the occurrence of cracking drops to an insignificant level when the sulphur content is reduced to the region of 0.010 per cent, (2) the effect of sulphur is increased by raising the level of phosphor, (3) lower contents of sulphur and phosphor must be maintained when the carbon content of steel is increased, and (4) a formula has been derived from their data and some earlier German data that $C\times(S+P)$ in per cent must be less than 0.007 for absence of cracking.

Wolstenholme et al[2] have also reported the solidification cracking of 2.25Cr-1Mo steel welds by basic manual metal-arc electrodes. The susceptibility to sulphur and phosphor induced solidification cracking was assessed in the report using Murex test and found to decrease markedly as the manganese content of the weld metals increased from 0.4 to 0.8%. Nowadays, chromium-molybdenum low alloy steels of low levels of sulphur and phosphor are widely supplied for production purposes in Japan.

The sulphur content of these steels is reduced to less than 0.010%, the phosphor content is normally less than 0.015%, and sometimes less than 0.010%.

Therefore, the authors have investigated in this research the hot crack susceptibility of the advanced chromium-molybdenum low alloys of low sulphur and phosphor of 1.25Cr-0.5Mo, 2.25Cr-1Mo, 3Cr-1Mo, and 5Cr-0.5Mo under the variation in carbon contents from 0.05 to 0.20 in per cent using the Varestraint Test (Longitudinal Varestraint Method).

## 2. Experimental Procedure

### 2.1 Materials Used

The chemical compositions of chromium-molybdenum low alloy steels used are shown in **Table 1,** which are classified into four typical groups of 1.25%Cr-0.5%Mo, 2.25%Cr-1%Mo, 3%Cr-1%Mo, and 5%Cr-0.5%Mo steels with each five carbon levels of about 0.05, 0.10, 0.12, 0.15 and 0.20%. The elements of manganese and silicon are set to constant values of about 0.6 and 0.3%, respectively, from the standpoint of practical use.

The impurities of sulphur and phosphor are aimed to be reduced to less than 0.01%, rsepectively. The

† Received on October 30, 1977
* Professor
** Nippon Steel Corporation Ltd.

**Table 1** - Materials used in this expeiment

| Type | No. | C | Si | Mn | P | S | Mo | Cr |
|---|---|---|---|---|---|---|---|---|
| 1.25%Cr-0.5% Mo | 1 | 0.05 | 0.27 | 0.61 | 0.010 | 0.008 | 0.49 | 1.30 |
| | 2 | 0.10 | 0.30 | 0.56 | 0.011 | 0.008 | 0.53 | 1.30 |
| | 3 | 0.12 | 0.29 | 0.60 | 0.007 | 0.007 | 0.50 | 1.28 |
| | 4 | 0.14 | 0.25 | 0.60 | 0.006 | 0.006 | 0.49 | 1.34 |
| | 5 | 0.21 | 0.26 | 0.58 | 0.007 | 0.008 | 0.50 | 1.34 |
| 2.25%Cr-1% Mo | 6 | 0.07 | 0.29 | 0.60 | 0.009 | 0.010 | 1.00 | 2.22 |
| | 7 | 0.08 | 0.30 | 0.57 | 0.008 | 0.008 | 1.03 | 2.29 |
| | 8 | 0.10 | 0.32 | 0.58 | 0.007 | 0.008 | 1.07 | 2.29 |
| | 9 | 0.14 | 0.27 | 0.59 | 0.009 | 0.007 | 1.03 | 2.28 |
| | 0 | 0.20 | 0.30 | 0.60 | 0.009 | 0.008 | 1.00 | 2.22 |
| 3%Cr-1%Mo | 11 | 0.06 | 0.32 | 0.63 | 0.009 | 0.009 | 1.00 | 2.94 |
| | 12 | 0.11 | 0.33 | 0.61 | 0.009 | 0.007 | 1.04 | 2.96 |
| | 13 | 0.12 | 0.29 | 0.61 | 0.006 | 0.007 | 1.07 | 3.20 |
| | 14 | 0.15 | 0.33 | 0.64 | 0.009 | 0.007 | 1.04 | 3.07 |
| | 15 | 0.18 | 0.32 | 0.57 | 0.007 | 0.008 | 1.04 | 2.94 |
| 5%Cr-0.5 % Mo | 16 | 0.06 | 0.34 | 0.69 | 0.009 | 0.009 | 0.53 | 4.96 |
| | 17 | 0.10 | 0.31 | 0.61 | 0.007 | 0.007 | 0.57 | 4.96 |
| | 18 | 0.12 | 0.33 | 0.59 | 0.009 | 0.007 | 0.54 | 4.94 |
| | 19 | 0.14 | 0.33 | 0.64 | 0.009 | 0.008 | 0.55 | 4.94 |
| | 20 | 0.18 | 0.35 | 0.60 | 0.010 | 0.008 | 0.55 | 4.95 |

specimens for the Varestraint test were machined 350 mm long by 50 mm wide on the test surface, with a thickness of 12 mm from each Heat No.

### 2.2 Testing Procedure

The Varestraint Test[3] which is called Longitudinal Varestraint Test in Japan has been used to determine the hot crack susceptibility of the steels throughout the experiments. The applied strain (augmented-strain) for the test specimen was varied 0.5, 1.0, 2.0 and 4.0% by using the bending blocks of different radius.

Two or three specimens were repeatedly tested for the same testing condition. Test welding was performed by bead-on-plate welding of conventional TIG arc (dcsp) under a pure argon shielding gas of 15 l/min.

The welding condition used was 300 amp of welding current, 17 volt of arc voltage and 10 cm/min of travelling speed.

Subsequent to the Varestraint Test, the total length of cracks, $L_T$ in mm, and the maximum length of cracks, $L_M$ in mm, on the surface of test specimen were examined and measured at 40X magnification in the as-welded and light-etched condition by taking the average of specimens tested. Moreover, the microstructures for some cracks were investigated after polishing to plate surface and etching with 5% nital reagent or saturated aqueous solution of picric acid with wetting agent.

Furthermore, the temperature distribution during solidification in welding was measured along weld centerline in order to decide the temperature range of the solidification brittleness of the steel, using a 0.3 mm diam tungsten-26% rhenium/tungsten thermocouples.

## 3. Experimental Results

A typical photograph of over-all view of the welded bead width after tested at 4.0% augmented-strain is shown in **Photo. 1**.

The solidification cracking is produced only within a narrow region directly behind the instantaneous position of the solid-liquid interface at the trailing edge of the weld puddle. Also microfissuring in the welded heat-affected zone is normally observed only

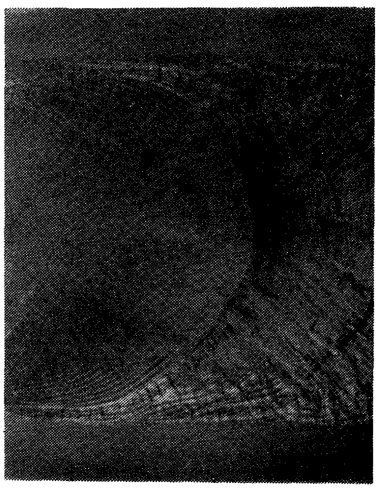


**Photo. 1** Over-all view of welded bead width after tested at 4.0% augmented-strain for 5Cr–0.5Mo–0.1C steel

in the region of the heat-affected zone at either side of the location of the weld puddle at the instant the augmented-strain is applied. Typical examples of the crack in the weld metal and the heat-affected zone are shown after metallographic examination in **Photo. 2** and **Photo. 3,** respectively.

**Photo. 2** Solidification crack in weld metal of 5Cr–0.5Mo–0.05C steel (×400)

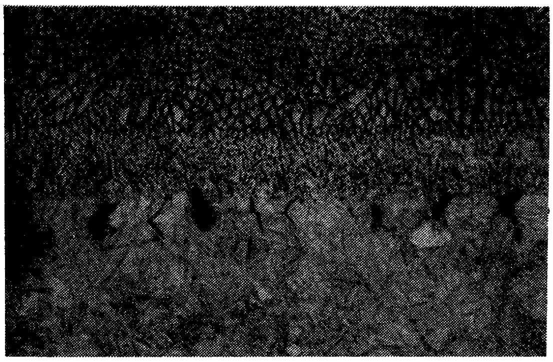


**Photo. 3** Liquation cracks in heat-affected zone of 2.25Cr–1Mo–0.2C steel (×100)

In **Fig. 1** the result measured for the total length of cracks, $L_T$, is shown against the augmented-strain for 1.25Cr-0.5Mo, 2.25Cr-1Mo and 5Cr-1Mo, respectively.

The minimum augmented-strain required to cause cracking is placed about 1.0% for lower carbon and in the range between 1.0% and 2.0% for higher carbon content steels. The $L_T$ is increased with an increase of the augmented-strain in general, though the $L_T$ in 1.25Cr-0.5Mo steels is too low to distinguish even in case of the 4.0% augmented-strain except for 0.2%C steel. In 1.25Cr-0.5Mo-0.2C steel the $L_T$ was exceptionally increased at the 4.0% augmented-strain, while it showed a rational length for the $L_T$ at the 2.0% or less angmented-strain levels. In 2.25Cr-1Mo and 5Cr-0.5Mo steels the $L_T$ is obviously lowered with an increase of carbon content.

The steels less than about 0.1% carbon, however, behave the same fashion for the change in the $L_T$.

It is generally said from Fig. 1 that the susceptibility

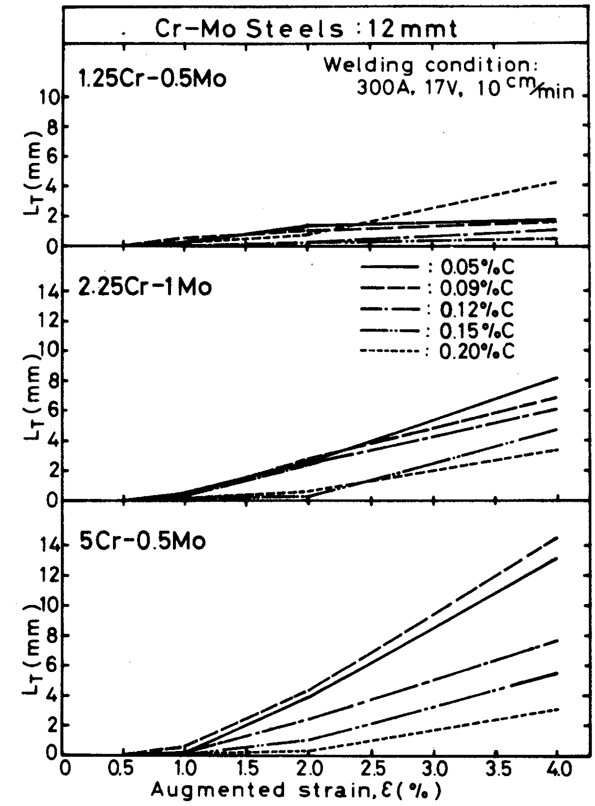



**Fig. 1** Effect of augmented strain on total length of cracks, $L_T$, for 1.25Cr–0.5Mo, 2.25Cr–1Mo and 5Cr–0.5Mo steels with various carbon contents

to solidification cracking is increased with increasing of chromium-molybdenum alloying elements at the same carbon level and with decreasing of carbon content at the same chrominum-molybdenum level steels except one example of the 4.0% angmented-strain in 1.25Cr-0.5Mo-0.2C steel.

The length of $L_T$ at the 4.0% augmented-strain is shown for each type of steel against carbon content in **Fig. 2.**

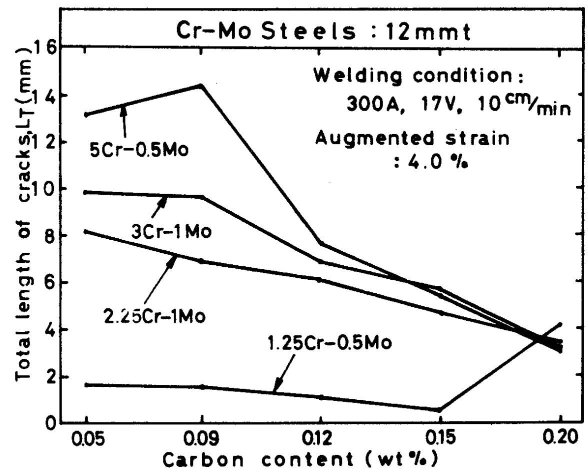



**Fig. 2** Effect of carbon content on total length of cracks, $L_T$, at 4.0% augmented-strain level

The susceptibility to solidification cracking is obviously low in 1.25Cr-0.5Mo steel. As mentioned in the above, the higher the chrominum-molybdenum alloy, the more the crack susceptibility in the steels less than 0.15% carbon level was. Moreover, the tendency is clear in lower carbon level less than 0.1%. In the higher carbon steels more than 0.12%, the crack susceptibility was shown almost the same value and then a gradual decrease with an increase of carbon for 5Cr-0.5Mo, 3Cr-1Mo and 2.25Cr-1Mo steels, and the crack susceptibility coincided at 0.2% carbon level for all four chrominum-molybdenum steels. The maximum length of crack, $L_M$, for each steel is shown against carbon content at the 4.0% augmented-strain level in **Fig. 3**.

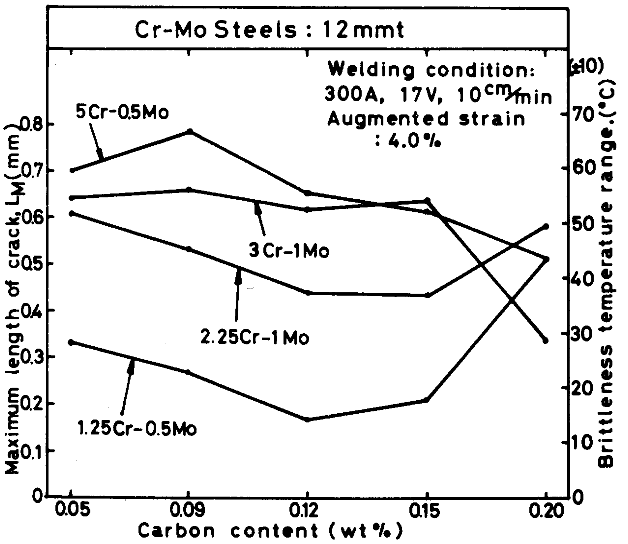



**Fig. 3** Effect of carbon content on maximum length of crack, $L_M$ and brittleness temperature range

The changing tendency in the length of the $L_M$ is similar to that of the $L_T$ in Fig. 2. On the right hand in the vertical axis the temperature range is simultaneously represented as the brittleness temperature range of the steel during weld solidification whose zero means the liquidus temperature at the liquid-solidus interface.

From the result the solidification brittleness temperature range is less than about 70°C and especially the range in 1.25Cr-0.5Mo steel is extremely narrow. Therefore, it is considered that the detrimental effects of sulphur and phosphor are anticipated to be very low in these steels used in this investigation.

## 4. Discussions

The equilibrium diagram of Fe-Cr-C ternary system is shown in **Fig. 4**. At near Fe corner it is predicted

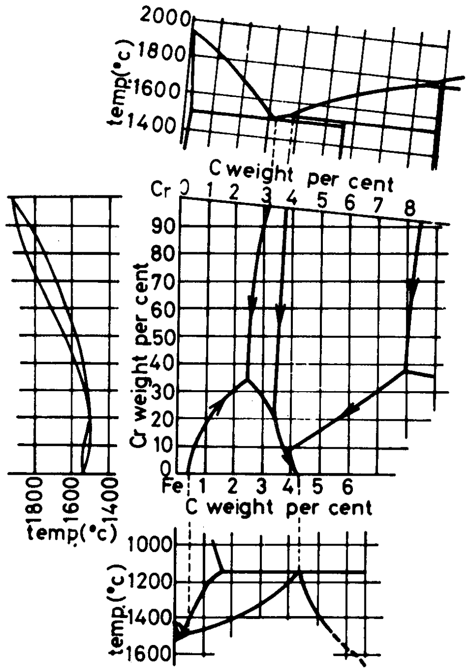



**Fig. 4** Fe-Cr-C ternary equilibrium diagram

that on the same chromium content the liquidus temperature of the steel will be depressed with an increase of carbon from the Fe-C binary diagram, while the solidus will be kept near the constant temperature due to the peritectic reaction within the range of carbon content in this investigation, then the solidification temperature will be decreased with an increase of carbon content. Moreover, it is predicted that on the same carbon content the liquidus temperature will be kept near the constant irrespective of an increase of chromium from the Fe-Cr diagram, while the solidus will be depressed with an increase of chromium. The authors have tried to illustrate the changing curves of the liquid composition of steel during solidification on the Fe-Cr-C ternary diagram near Fe corner. The results are shown in **Fig. 5(a)**. Each changing curve in liquid composition is given by[4)]

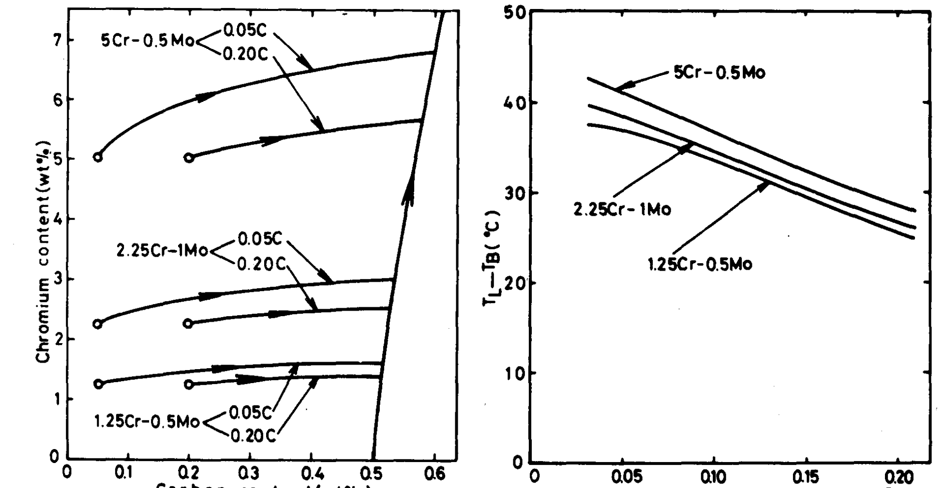
$$C_c^l = \left\{ \frac{C_{cI}}{C_{crI}^{(1-K_c)/(1-K_{cr})}} \right\} \cdot C_{cr}^{l(1-K_c)/(1-K_{cr})} \quad (1)$$

where, $C_c^l$ and $C_{cr}^l$: carbon and chromium concentration in the remaining liquid, respectively.

$C_{cI}$ and $C_{crI}$: carbon and chromium content in steel, respectively.

$K_c$ and $K_{cr}$: distribution coefficients of carbon and chromium, 0.2 and 0.9, respectively.

From the result of the illustration in Fig. 5(a), it is suggested that the liquid composition in the last stage for the steel whose carbon is lower or chromium is higher will be reached to lower temperature zone




(a) Examples of changing curve in composition given by: $C_L^C = \{C_{Cr}/C_{Cr}^{L}(1-kC)(1-kCr)\} C_{Cr}^{L(1-kC)/(1-kCr)}$, $kC=0.2$, $kCr=0.9$

(b) Temperature range between liquidus($T_L$) and peritectic point($T_B$)

**Fig. 5** Effect of concentration of Cr and C on locus of solidification process and solidification temperature range

on the peritectic reaction line. Furthermore, the thermal analyses of these steels were tried to measure the liquidus and the bulk solidus temperatures using a 0.5 mm diam Pt-Pt/13%Rh thermocouples. The solidification temperature range, $T_L$-$T_B$ is shown in Fig. 5(b) as a result. This will support the above consideration qualitatively. Moreover the susceptibility of the solidification cracking as shown in Fig. 1 will be also qualitively explained, that is, the increase of chromium or the decrease of carbon makes chromium-molybdenum steel susceptible to cracking. One of the authors, Matsuda, has reported with his colleague the susceptibility of the solidification cracking of various constructional steels[5], HY-type high tension steels[6] and austenitic stainless steels[7] using the Varestraint test.

From these results and some other experimental results, the authors have a feeling at present that the criterion of the solidification crack susceptible steel is placed on 10 mm or more in the total length of cracks, $L_T$ at the 4.0% augmented-strain level on 12 mm thick plate for welding condition of 250 amp, 17 volt, 10 cm/min for austenitic stainless steels and high nickel alloys or 300 amp, 17–20 volt, 10 cm/min for plain and low alloy ferritic steels. For the steels more than 10 mm in the $L_T$, the authors pay a doubt for occurring the solidification crack in the welding for actual construction purposes and for the steels more than 20 mm, a great anxiety for occurring that. The steels which were troubled for the solidification cracking during welding in actual production in industry have mostly shown about more than 20 mm in the $L_T$ at the 4.0% angmented-strain of the Varestraint test from the author's experiences. Judging from this point of view the authors think that special attention for solidification cracking must be paid at most for low carbon (less than 0.1%C) 5Cr-0.5Mo and 3Cr-1Mo steels whose sulphur and phosphor contents are less than 0.01%, respectively.

## 5. Conclusions

The Varestraint test (Trans-Varestraint test) was done to evaluate the solidification crack susceptibility for the low sulphur and phosphor 1.25Cr-0.5Mo, 2.25Cr-1Mo, 3Cr-1Mo and 5Cr-0.5Mo steels. The following conclusions were obtained;

(1) The susceptibility to solidification cracking in chromium-molybdenum steel is increased with an increase of chromium-molybdenum alloying elements at the same carbon level, and with a decrease of carbon content at the same chromium-molybdenum steels. Therefore, the order of the crack susceptibility is arranged as 5Cr-0.5Mo, 3Cr-1Mo, 2.25Cr-1Mo and 1.25Cr-0.5Mo steels. The crack susceptibility is very low in 1.25Cr-0.5Mo steel in comparison with the other steels.

However, for the high carbon steel of 0.2% in 1.25Cr-0.5Mo steel, the susceptibility was exceptionally high at the large amount of augmented-strain as the 4.0%, while it was rationally low in the augmented-strain less than 2.0%.

(2) From the total length of cracks at the 4.0% angmented-strain level, the crack susceptibility in 5Cr-0.5Mo, 3Cr-1Mo and 2.25Cr-1Mo steels was to be the same when carbon content was increased more

than 0.12%. Moreover, at carbon content of 0.2% that of 1.25Cr-0.5Mo steel was also to be in accord with that of these other steels.

(3) Judging from the result of the Varestraint test at the 4.0% augmented-strain and the authors' experiences in the past works, the anxiety for the weld solidification cracking should be paid at most for the low carbon (less than 0.1 %C) 5Cr-0.5Mo and 3Cr-1Mo low alloy steels.

### References

1) F. J. Wilkinson et al.: "Factors Affecting Weldability of High Strength 1 per cent Chromium-Molybdenum and Other Steels", Weld Metal Fab, 26 (1958) 5, 171–184
2) D. A. Wolstenholme et al.: "Effect of Manganese on Solidification Cracking in 2CrMo Manual Metal-arc Weld Metal", Weld & Met Fab, 40 (1972) 2, 59–67
3) W. F. Savage et al.: "The Varestraint Test", W.J., 44 (1965) 10, 433-S
4) H. Nakagawa, F. Matsuda, T. Senda: "Effect of Sulphur on Solidification Cracking in Weld Metal of Steel (Report 2)", Trans. JWS, 5 (1974) 2, 84–89
5) For example, T. Senda, F. Matsuda et al.: "Fundamental Investigations on Solidification Crack Susceptibility for Weld Metals with Trans-Varestraint Test, Trans. JWS, 2 (1971) 2, 1–22
6) H, Kihara, F. Matsuda: "Varestraint Test for Hot Crack Susceptibility of HY-type High Strength Steels", Trans. JWRI, 2 (1973), 2, 83–95
7) Y. Arata, F. Matsuda, S. Saruwatari: "Varestraint Test for Solidification Crack Susceptibility in Weld Metal of Austenitic Stainless Steel", Trans. JWRI, 3 (1974) 1, 79–88