Grooved Copper Mold Testing of Inconel Alloy 600

A restrained cast pin cracking test has been found to predict weld metal cracking sensitivity based on dilution and on the cracking sensitivities of the base and filler metals being welded

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ABSTRACT. It has been found that NiCrFe Alloys 600 and EN82 exhibit a large variation in cracking sensitivity between heats. A simple test has been developed which accurately predicts material cracking sensitivity. It is called the grooved copper mold test. In it, a sample of the material to be tested is induction melted and cast into cylindrical copper molds. The shape of the induction coil is such that the sample levitates during melting, thus avoiding contamination from a crucible. The geometry of the mold is designed such that the cooling rate and shrinkage strains of the cooling cast specimen approximate those of a weld.

The results which will be discussed include acceptability testing of both Alloy 600 and EN82, the relationship between cracking sensitivity and base metal to filler dilution in the weld nugget, and the relationship between the cracking index obtained from the grooved copper mold test and the results obtained from test welds.

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Introduction

Variations have been found in weld nugget cracking sensitivity when welding identical configurations with identical processes and using different heats of Inconel Alloy 600 and EN82 filler wire. Therefore, a program was initiated to establish a testing procedure which could predict the cracking sensitivity of various heat combinations prior to making an actual weld.

The "cast pin tear test" was developed by F. C. Hull in 1959 (Ref. 1). In this test, specimens of various compositions were levitation melted and cast into copper molds with various height to diameter ratios. The larger the ratio of height to diameter the greater the restraint and the greater the tendency to produce a crack. A series of molds with increasing ratios were used and the measure of cracking sensitivity was the mold number at which cracking began.

In 1963, the Bettis Laboratory began to evaluate the fissuring sensitivities of different heats of Inconel Alloy 600. The Gleeble hot ductility test was used and a correlation of fissuring sensitivity with hot ductility response was developed (Ref. 2). However, in this test only undiluted filler metals were used. To provide test samples with various base metal/filler dilutions for Gleeble testing a levitation melting apparatus similar to that of Hull (Ref. 1) was used to cast 1/4 in. diam by 4 in. long pins. The initial work was unsuccessful, because even though smooth, unrestrained molds were used, many of the pins developed a large crack.

The problem was identified as coming from restraint developed by the metal in the pouring cup on the top of the mold and a flash of metal on the bottom of the mold. Short pouring to eliminate excess metal in the pour cup resulted in a shrinkage pipe in the cast pin, which was also undesirable.

It was theorized that if a threaded mold were used, the restraint would be developed in small increments, uniformly over the length of the cast pin. Experiment did in fact confirm this approach. No large cracks developed in the threaded pins. However, careful examination revealed numerous fine cracks occurred between the threads which again made the pins undesirable for Gleeble testing.

A careful measurement of the sizes and number of cracks indicated that a correlation existed between cracking in the cast pins and fissuring sensitivity during welding. This observation eliminated the necessity of

Gleeble testing to predict fissuring sensitivity during welding. This work was reported by Talento (Ref. 3). However, identification and measurement of the cracks between the threads is very difficult and tedious. It was decided to try a grooved copper mold with grooves spaced one inch apart to develop restraint. This new mold was evaluated and found to successfully predict fissuring sensitivity during welding.

Test Procedure

Briefly, the grooved copper mold test is run as follows:

(1) Accurately weighed quantities of the desired base and filler metal are tack welded together to form specimens of the desired base/filler dilution. A test consists of five specimens, each weighing 32 g. Typical specimens are shown in Fig. 1.

(2) The specimens are levitation melted under argon atmosphere and cast into grooved copper molds. A mold is shown in Fig. 2 and the levitation melting apparatus is shown in Fig. 3. As-cast specimens are shown in Fig. 4.

(3) The surfaces of the cast specimens are examined at 25X in order to obtain the fissuring index of the base-filler alloy at the dilution being studied.

The procedure used in evaluation is as follows:

(a) Cracks are divided into categories with the following weighting factors for each category:

Category	Size, in.	Weighting factor
Small	0–1/8	1
Medium	1/8–3/16	2
Large	3/16–1/4	3
Extra large	Over 1/4	5

For each specimen the number of cracks of each category is counted. This number is then multiplied by the weighting factor corresponding to the category. These weighted totals for each category are added to obtain a fissure index for each specimen.

(b) The fissure index for the five specimens is added.

(c) The fissure index obtained in (b) is multiplied by six to obtain the grooved copper mold (GCM) index. This multiplication by a factor of 6 is a result of reducing the number of pins in a test from 30 down to 5. Initial work was done with 30 specimens, but as the reproducibility of the test was evaluated, the number of pins per evaluation was reduced to 5. In order to keep the same GCM index the present results on 5 pins are multiplied by 6.

Fig. 1 — Grooved copper mold samples before levitation melting

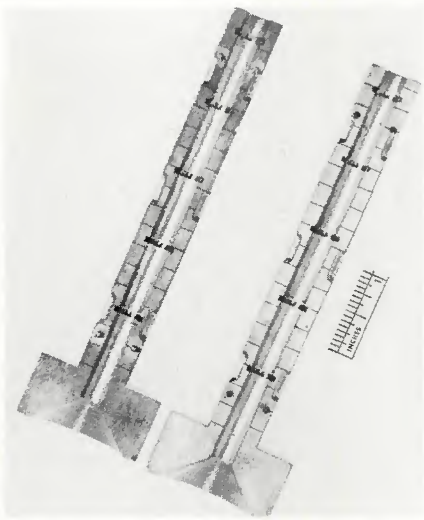

Fig. 2 — Grooved copper mold in open position

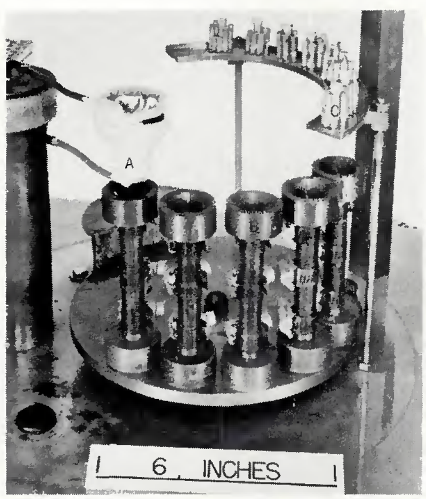

Fig. 3 — Levitation melting assembly: A-work coil; B-grooved molds; C-specimens

Method of Calculating Dilution

Dilution in welding is calculated by:

$$\% \text{ Dilution} = \frac{W_n - W_f}{W_f} \times 100$$

$$= \frac{W_b}{W_f} \times 100$$

where W_n = weight of weld nugget, W_f = weight of filler metal and W_b = weight of base metal.

Statistical Analysis of Test

In order to have confidence in the results of grooved copper mold testing, it had to be ascertained that the test is statistically valid, that the type of statistics which were applied to the test are correct, and that mold characteristics did not vary over a period of time.

Statistical theory indicates that the GCM index should be a random variable obeying normal or Gaussian statistics. In order to test this theory 60 specimens of Alloy EN82 Heat #1000 were used. The fissure index for each specimen was multiplied by thirty (this should produce a GCM index equivalent to that obtained by multiplying a five specimen total by six). The frequency of observation for a given GCM index was then plotted versus the GCM index in Fig. 5. As expected, a curve resembling that of a Poisson distribution was obtained. The reason that the curve is Poisson rather than Gaussian is that a limited number of points (60) was used to construct it. As the number of points is increased, the curve would more nearly approach Gaussian until, at very large numbers, the curve would be Gaussian. So therefore, the use of Gaussian statistics is assumed to be correct.

To calibrate a new set of molds, thirty specimens are cast in six groups of five. A fissure index is then obtained for each set of five specimens. The calibration values obtained for two sets of molds, the "A" and "B" mold sets are shown graphically in Figs. 6A and 6B. If a set of molds exhibits excessive variability between molds the data are replotted as in Figs. 7A and 7B so that each set of data consists of five specimens cast in one mold. It can be seen that mold number 4 in mold Set "A" gives somewhat lower GCM indices than the other four molds. This mold was carefully examined and no difference could be found between it and the other molds in mold Set "A". It should also be noted that when five pins are cast to make a test set, molds 1 thru 5 are always used. Hence, the effect of mold 4 is always the same. A comparison of the "A" set of molds and the "B" set of molds is shown in Fig. 8 for the average of 5 tests (30 specimens). Here we see that the comparison of average GCM indices between mold sets "A" and "B" are quite close, that is, 386 versus 389. Therefore, Mold Set "A" is considered identical to Mold Set "B".

Each mold set is calibrated before it is used. Once a mold set is in use, every tenth test is a calibration which consists of a set (5 specimens) of Alloy EN82 Heat No. 1374 to be sure mold characteristics do not vary with time.

It should be noted that if,

$2\sigma_1$ = Two standard deviations based on 1 specimen of population distribution (Fig. 5)

$2\sigma_5$ = Two standard deviations of average of 5 specimens

$2\sigma_{30}$ = Two standard deviations of average of 30 specimens

then according to statistical theory,

$$2\sigma_5 = \frac{2\,\sigma_1}{\sqrt{5}}$$

$$2\sigma_{30} = \frac{2\sigma_5}{\sqrt{6}} = \frac{2\sigma_1}{\sqrt{30}}$$

$2\sigma_1$ can be obtained from Fig. 5 as 210.

Fig. 4 — Finished grooved copper mold castings

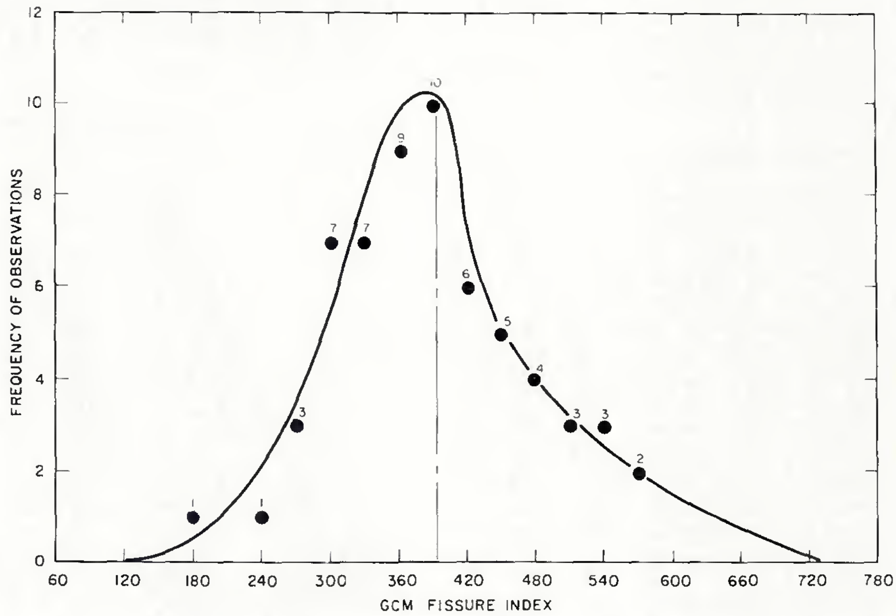

Fig. 5 — Population distribution of GCM fissure index for single specimens from EN82 heat no. 1000

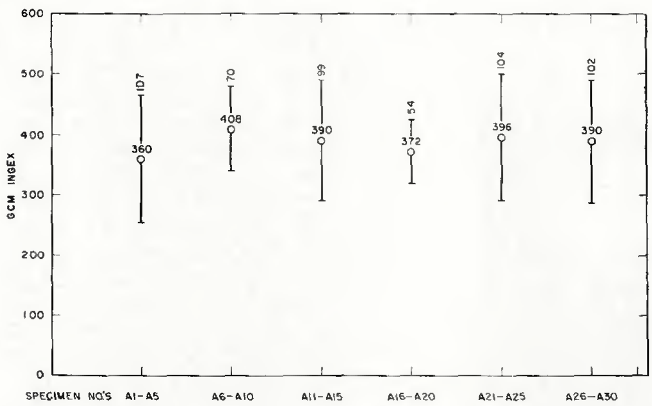

Fig. 6A — GCM index showing mold calibration of the mold set A, using EN82 heat no. 1000

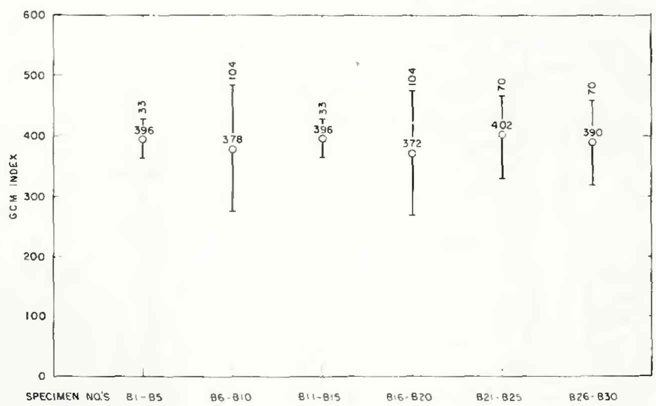

Fig. 6B — GCM index showing mold calibration of the mold set B, using EN82 heat no. 1000

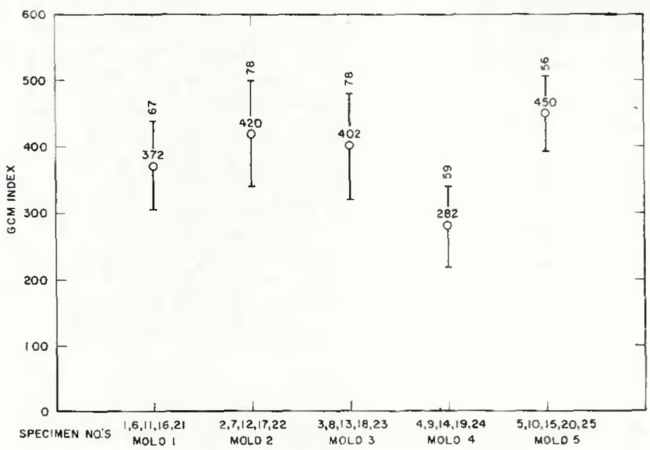

Fig. 7A — GCM indexes showing mold to mold variations of mold set A

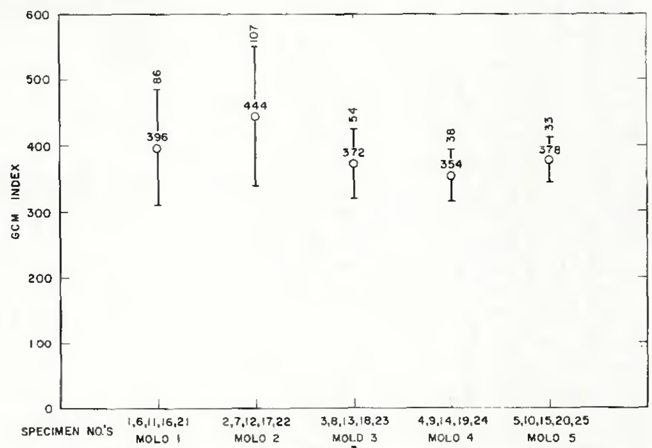

Fig. 7B — GCM indexes showing mold to mold variations of mold set B

$2\sigma_5$ is estimated as the average of the $2\sigma_5$'s for six runs in Fig. 6A as 89.

$2\sigma_{30}$ is estimated by the 30 specimens run as one test in Fig. 8 as 38. So then,

$2\sigma_5$ should be $\frac{210}{\sqrt{5}} = 95$; experimentally $2\sigma_5 = 89$

$2\sigma_{30}$ should be $\frac{210}{\sqrt{30}} = 38$; experimentally $2\sigma_{30} = 38$

Results and Discussion

Using the grooved copper mold test, three different heats of Inconel Alloy 600 base metal were tested with various heats of filler metal over a range of dilutions. The results are shown in Figs. 9A, 9B and 9C. It can be seen that for all fillers a smooth curve can be drawn through the various dilutions to the base metal index. This indicates that there is a relation, probably quadratic, between the susceptibility to cracking as measured by the grooved copper mold index and dilution. The filler metals have intentional additions of manganese and columbium which reduce weld metal cracking sensitivity, whereas the base metals do not have these additions. Hence, as the filler metal composition is diluted by the base metal, the cracking sensitivity of the weld nugget increases approaching the cracking sensitivity of the base metal.

The weld nugget cracking index, which is the index of importance, is dependent on the cracking index of the base metal, the cracking index of the filler, and dilution.

To determine the usefulness of the nugget GCM index in predicting cracking sensitivity in welds, nine test welds were evaluated by this technique. They were full penetration single pass welds made in approximately 0.090 in. thick Inconel Alloy 600. One filler metal heat with an index of 1098 was used to weld five base metal heat combinations. The nugget GCM indices were obtained by drawing typical curves between the filler and base indices and using a dilution of 325% as shown in Fig. 10. The welds were evaluated by liquid penetrant testing followed by metallographic evaluation of all indications. The maximum random crack depth found in this metallographic examination is shown as a function of nugget GCM index in Fig. 11. A correlation was found between crack depth and nugget index.

This correlation demonstrates the credibility of this analysis procedure. However, caution should be exercised in using exact numbers to predict cracking since these data are for one particular weld joint design welded by one particular process. For other weld joint designs and processes other factors, such as stress will be different,

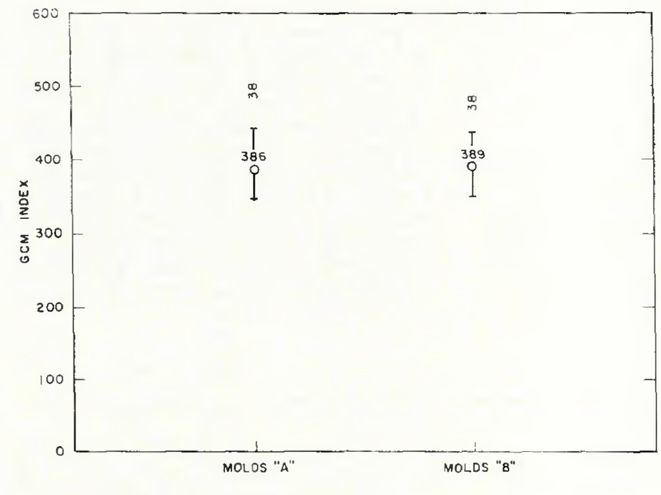

Fig. 8 — GCM indexes showing a comparison between mold sets A and B based on 30 specimens

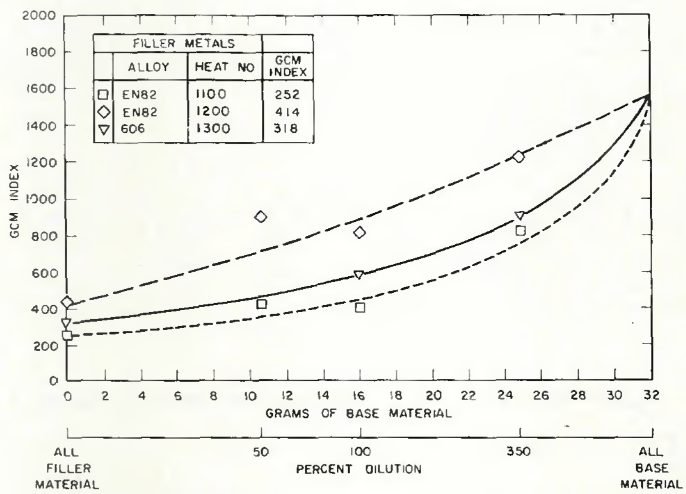

Fig. 9A — GCM indexes of various filler metals as a function of dilution with Alloy 600 base metal, heat 2200 (GCM index 1450)

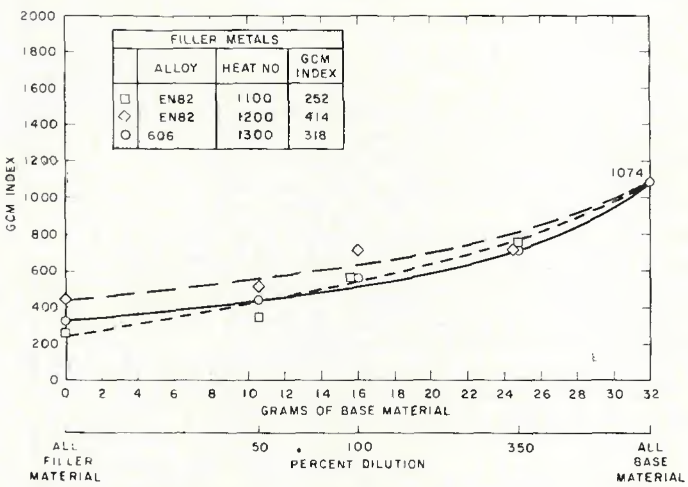

Fig. 9B — GCM indexes of various filler metals as a function of dilution with Alloy 600 base metal, heat 2100 (GCM index 1074)

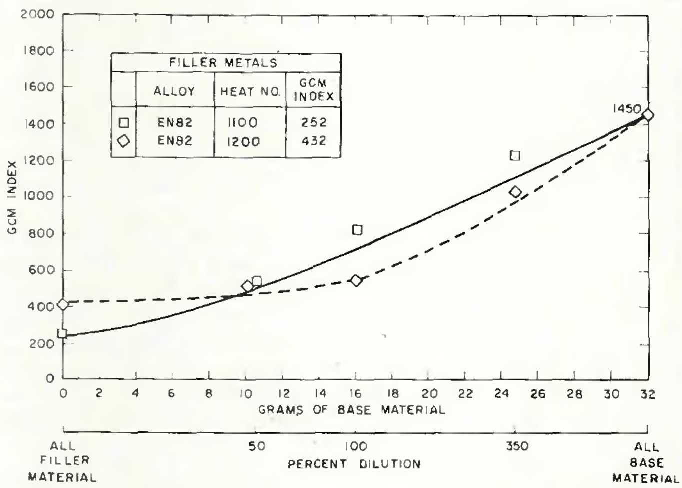

Fig. 9C — GCM indexes of various filler metals as a function of dilution with Alloy 600 base metal, heat 2100 (GCM index 1450)

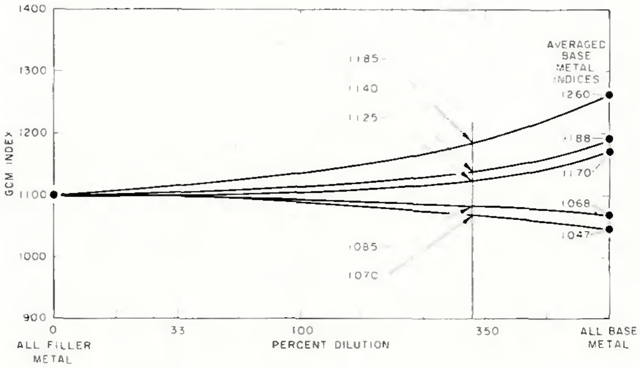

Fig. 10 — Estimate of nugget GCM indexes from average base metal indexes and dilution for test welds

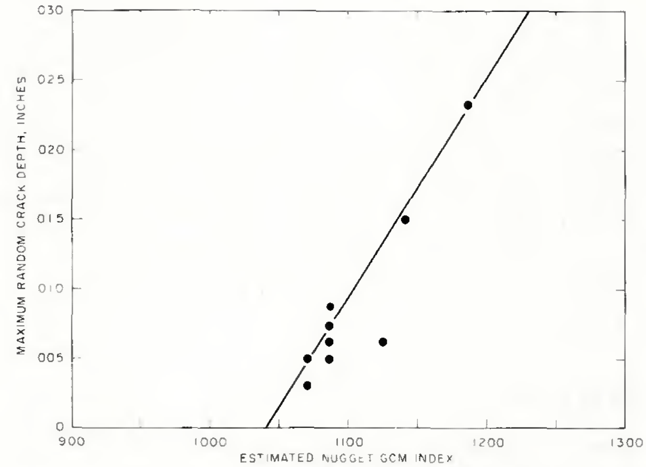

Fig. 11 — Maximum random crack length vs estimated nugget GCM index for test welds

and the curve on Fig. 11 could shift to higher or lower indices.

Conclusions

1. A grooved copper mold weldability test has been developed to predict cracking sensitivities of Inconel Alloy 600 and EN82.

2. The weld nugget cracking index is a function of base heats, filler heats and dilution, and increases with increasing dilution approaching the base metal index.

3. The weld nugget cracking index has been found to correlate with crack depth found in a series of actual test welds.

4. Problems encountered with weld cracking Alloy 600 with EN82 filler can be solved by changing base metal heats, changing filler metal heats, or changing the welding process to reduce base:filler dilution.

Acknowledgement

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