INTERRELATIONSHIP BETWEEN MATERIAL STRENGTH AND COMPONENT DESIGN UNDER ELEVATED TEMPERATURE FOR FBR

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Abstract

Structural design under elevated temperature for fast breeder reactor plant is very troublesome compared to that of for lower temperature. This difficulty can be mainly discussed from two different stand points. One is design and design code, another is material strength.
Components in FBR are operated under creep regime and time dependent creep behavior should be evaluated properly. This means the number and combinations of design code and material strength are significantly large and makes these systems very complicated.
Material selection is, in no words, not a easy job. This should be done by not only material development but also component design stand point.
With valuable experience of construction and research on FBR, a lot of information on component design and material behavior are available. And it is a time to choose the "best material" from the entire stand points of component construction.

1. **Introduction**

Structural design under elevated temperature for fast breeder reactor plant is very troublesome compared to that of for lower temperature. This difficulty can be mainly discussed from two different stand points. One is design and design code, another is material strength.

Components in FBR are operated under creep regime and time dependent creep behavior should be evaluated properly. This means the number and combinations of design code and material strength are significantly large and makes these systems very complicated.

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Described in this paper our stand. point for material selection for future plant components.

2. **What is a "Good Material" ?**

What is a definition of "Good Material" for FBR components ? If you can give a simple distinctive answer, material selection for newly designed plant seems easy.

ASME Boiler and Pressure Vessel Code Case N-47 gives us creep rupture time of several materials. You can easily find allowable creep rupture time for 316SS is larger than that of for 304SS by about one figure. From this point, 316SS seems to be better than 304SS.

In FBR components, most creep damage is counted during relaxation by residual stress caused by abrupt thermal transient. It can be expected relaxation rate or strain rate will play an important role in FBR creep damage.

If you take this point into account, no significant differences can be found between these two materials. Assuming they have equal characteristic in creep, which is a better material ?

This is only a typical example to say material selection for FBR is not so simple work.

3. **How to evaluate creep damage ?**

Paragraph T-1433 of ASME Boiler and Pressure Vessel Code Case N-47 shows us creep damage evaluation methods.

In one case, 1.25Sy/K' should be compared to creep rupture curve and creep damage $\int_0^t \frac{dt}{Td}$ can be calculated. Examples of the calculation are shown in Table-1.

However, as stated in the previous chapter, dominant creep damage in FBR components is suffered through relaxation.

To know creep damage during relaxation, relaxation calculation was carried out with initial stress 1.25Sy at 500°C and 550°C.
Relaxation curves are shown in Fig. 1. Creep damage is tabulated in Table-2.
Compare this table with Table-1. What we see by these calculations is the reverse relation of creep damage of 304SS and 316SS. Only at 500°C, 10^4 hr's damage of 304SS is slightly larger than that of 316SS.
Creep damage is one of most characteristic features in FBR structural design and important stand point for material selection.
This comparison indicates material which is "stronger" in creep is not always better than the other and necessity of study of design standard for material selection.

4. Creep damage and material Constant

You can easily estimate the creep damage in the case it depends on only creep rupture time.
When you take into account the effects of relaxation, this is not so simple.
Here we have studied the effect of strain rate onto creep damage.
Three cases of strain rate are compared in Fig. 2 and Table-3.
Case 1 is original 304SS as described in previous chapter. As for cases 2 and 3, five times and one fifth of strain rate of original 304SS are assumed.
Fig. 2 shows the difference of relaxation behavior. We can see the slower strain rate, the lesser relaxation.
Comparison of creep damage is on Table-3 and significant differences can be found.
This means, from the view point of creep damage, the higher strain rate is desirable and material development work should take this point take into account.

5. **Effects of yield point on buckling behavior**

Plastic buckling behavior is one of typical example where yield point plays an important role.
The analytical buckling behavior of straight tube of heat exchanger say two things. First, allowable maximum thermal load has direct relation with yield point as expected.
Second one is a significant difference between the results by analysis and experiment event though the analyses were carried out by using average material constants.
Generally speaking, it is well known the yield point of the tube is significantly higher than that of the plate or forging. Thus, in some cases it is very effective to have separate material strength standard for these material types of fabrication.

What we see in this study is an importance of type of material fabrication when we discuss "material".

6. **Choice of material from view points of component design**

Structural designs of FBR components have close connection with material strength standard as stated in previous chapter.

At the stage of early FBR plant construction, generally speaking, material selection was performed without sufficient corelation of design and mterial research and development.

Main purposes of research and developments of such FBR materials are concentrated on material improvements and data accumulation.

However, it is a time that material selection have to be carried out from its early stage with intensitive evaluations of component design.

7. Parameters of Material Selection

We have a lot of parameters for material selection. In this chapter are described major parameters for FBR components material selection.

7.1 Strength under Elevated Temperature

They say we have not small area where structure does not satisfy the design code on an elastic basis. To complete structural design under elevated temperature easily is a major concern of FBR component designers.

Among them creep-fatigue damage is the most difficult area.

Improvements of creep-fatigue strength of materials area being waited by a lot of designers.

Here, care should be taken by material people that materials which have stronger creep strength do not always have advantages when evaluated by a certain design code as stated in chapter 3.

Strain rates, yield points and other material constants should be taken into account at the same time.

Material people as well as designers has to study the points of design code and component design and should propose FBR component design code from the stand point of material developments.

7.2 Environmental Effects

Liquid sodium, nitrogen and argon gases and water/steam are representative environments in FBR components.

A lot of troubles experienced in FBR seem to be caused by environmental effects.

For thin wall heat transfer tubes in heat exchanger, curbulization and decurbulization, corrosions, frettings and etc. are main concerns. Self-welding, embrittlement under elevated temperature can not be neglected.
Potential of stress corrosion cracking for steam generator has to be sufficiently checked before the final determination of the material.

7.3 Productivity of Different Type of Material

Generally, the research work on a certain material begins in most cases with plate in middle size thickness because of easy material handling in tests.
However, the points we have to pay an attention are that we need different types of materials from thin tubes to very thick forgings.
The characteristics of these types of materials differ from type to type.
And in some cases, for example, we can not get thick forgings with satisfactory specifications.

7.4 Fabrication

A stage of component fabrication is important point which material people be apt to miss the discussions.
Assume, you have two materials of austenitic steel and ferritic steel as candidates.
There is a significant difference in component fabrication from both materials. That is heat treatment.
If you use austenitic steel, you don't need stress relief heat treatment.
When your selection is ferritic steel, you have to perform pre and post weld heat treatment.
This does not seem so important as far as you are thinking in laboratory.
However, in shops or sites yes or no of heat treatment will affect the advantage of both materials.
Necessary cleanness and care for material handling are other points of discussion. These points have to be taken into account for material selection.

7.5 Cost

Recently, construction cost of nuclear plants has been required to reduce because of energy status in the world. FBR is not an exemption.
Material has close connection with plant cost.

If advantageous material is applied to only components like intermediate heat exchanger or steam generator, the effect on cost is not significant.
However if it is used for main components including piping system the effect will be quite large.

8. Material Selection for Demonstration Plant

We have already determined materials for Monju. Our current efforts of research and developments on material selection are for the demonstration plant even though the work for improvement of Monju material is continuing.
From the view points of material selection, a steam generator is a major concern.
Materials of almost all primary circuit are austenitic stainless steels, however, we see different material selections of steam generators in different FBR countries.
Some of these materials have been already used for plants and some others are only planned.
They are austenitic stainless steels, 2¼Cr-Mo, 9Cr-1Mo, 9Cr-2Mo, 12Cr-1Mo and alloy 800, etc.
Table-4 shows the tube materials for steam generators of world FBR plants.
For future plants, only candidate materials which author could study are described.
This table imply relatively wide range material selection for steam generator compared to those of primary circuits components which are austenific stainless steels, in general.
What are the reasons of these selections ?
The first one is the difficulty of structural design of steam generator under elevated temperature. In some cases the design does not always satisfy code requirements on an elastic basis.
Troubles of steam generators seem to be the most cases of FBR troubles under plant operations.
These facts imply that material selection of steam generators is the most troublesome work in FBR.

9. Method for Material Selection

Under these circumstances, what is a method for material selection ?
With valuable experiences of construction and research on FBR, a lot of information on component design and material behavior are available.

And it is a time to choose the "best material" from entire stand points of component construction.
Fig. 3 shows a typical example of flow diagram for material selection.
The flow diagram is not always the same in accordance with the environmental condition, however, to make an appropriate flow for this job and proceed the plan by necessary time are the most important.
We believe this is the best case to progress the real material selection job.

Table-1 Creep Damage (1) *1

material	temperature (°C)	Sy (kg/mm^2)	1.2 Sy/k' (kg/mm^2)	Td (hr)	Dc *2
304SS	500	11.1	15.4	2.0×10^5	1.1
	550	10.8	15.0	1.1×10^4	19.1
316SS	500	11.8	16.4	1.2×10^6	0.18
	550	11.4	15.8	4.0×10^4	5.3

*1 based on par. T-1433 (g)(2), ASME C.C. N-47.

*2 Duration of creep is 2.1×10^5 hr.

Table-2 Creep Damage (2) *1

material	temperature (°C)	Dc	
		1×10^4 hr	2.1×10^5
304SS	500	0.011	0.060
	550	0.027	0.087
316SS	500	0.008	0.096
	550	0.052	0.26

*1 Calculated along relaxation curve initial stress 1.25 Sy.

Table - 3 Creep Damage *1
(effect of strain rate)

*2 Strain rate	Dc	
	1×10^4 hr	2.1×10^5 hr
1/5	0.169	0.904
1	0.027	0.087
5	0.003	0.006

*1 at 550°C 304SS

*2 normalized by reference value

Table 4 SG Tube Meterial of World FBR Plants

<table>
<tr><th rowspan="2">Country</th><th rowspan="2">Plant</th><th rowspan="2">Output (MWe)</th><th rowspan="2">Temp. of Main Steam (°C)</th><th colspan="2">Tube Material *</th></tr>
<tr><th>Evaporator</th><th>Super Heater</th></tr>
<tr><td>USA</td><td>CRBRP</td><td>300</td><td>483</td><td colspan="2">$2\frac{1}{4}$ Cr · 1Mo (Ann)</td></tr>
<tr><td rowspan="3">France</td><td>Phenix</td><td>251</td><td>510</td><td>$2\frac{1}{4}$ Cr · 1Mo
$2\frac{1}{4}$ Cr · 1Mo-Nb</td><td>321SS</td></tr>
<tr><td>Super Phenix 1</td><td>1,200</td><td>515</td><td colspan="2">Alloy 800</td></tr>
<tr><td>Super Phenix 2</td><td></td><td></td><td colspan="2">9Cr2MoNb · V · Mn or Alloy 800</td></tr>
<tr><td rowspan="2">UK</td><td>PFR</td><td>270</td><td>516</td><td>$2\frac{1}{4}$ Cr·1Mo-Nb</td><td>316SS</td></tr>
<tr><td>CFR</td><td>1,300</td><td>490</td><td colspan="2">9Cr · 1Mo</td></tr>
<tr><td rowspan="2">West Germany</td><td>SNR 300</td><td>312</td><td>500</td><td colspan="2">$2\frac{1}{4}$ Cr · 1Mo-Nb-Ni</td></tr>
<tr><td>SNR-2</td><td>1,000</td><td>500</td><td colspan="2">$2\frac{1}{4}$Cr·1Mo-Nb-Ni or 12Cr·1Mo or Alloy 800</td></tr>
<tr><td rowspan="2">USSR</td><td>BN350</td><td>150</td><td>435</td><td colspan="2">$2\frac{1}{4}$Cr·1Mo</td></tr>
<tr><td>BN600</td><td>600</td><td>505</td><td>$2\frac{1}{4}$Cr·1Mo</td><td>Austenitic stainless</td></tr>
</table>

* For future plants, candidate material studied by the author

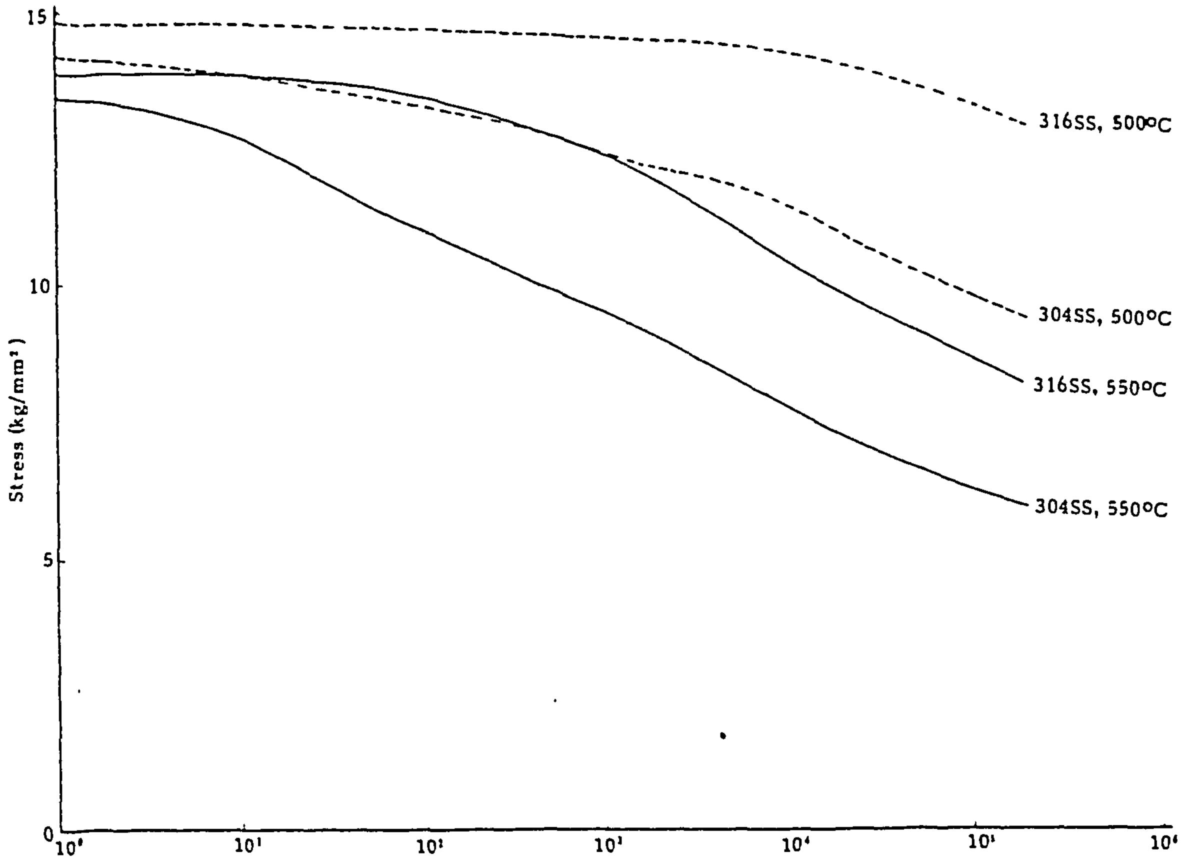

Fig. 1 Relaxation Curve of 304SS and 316SS

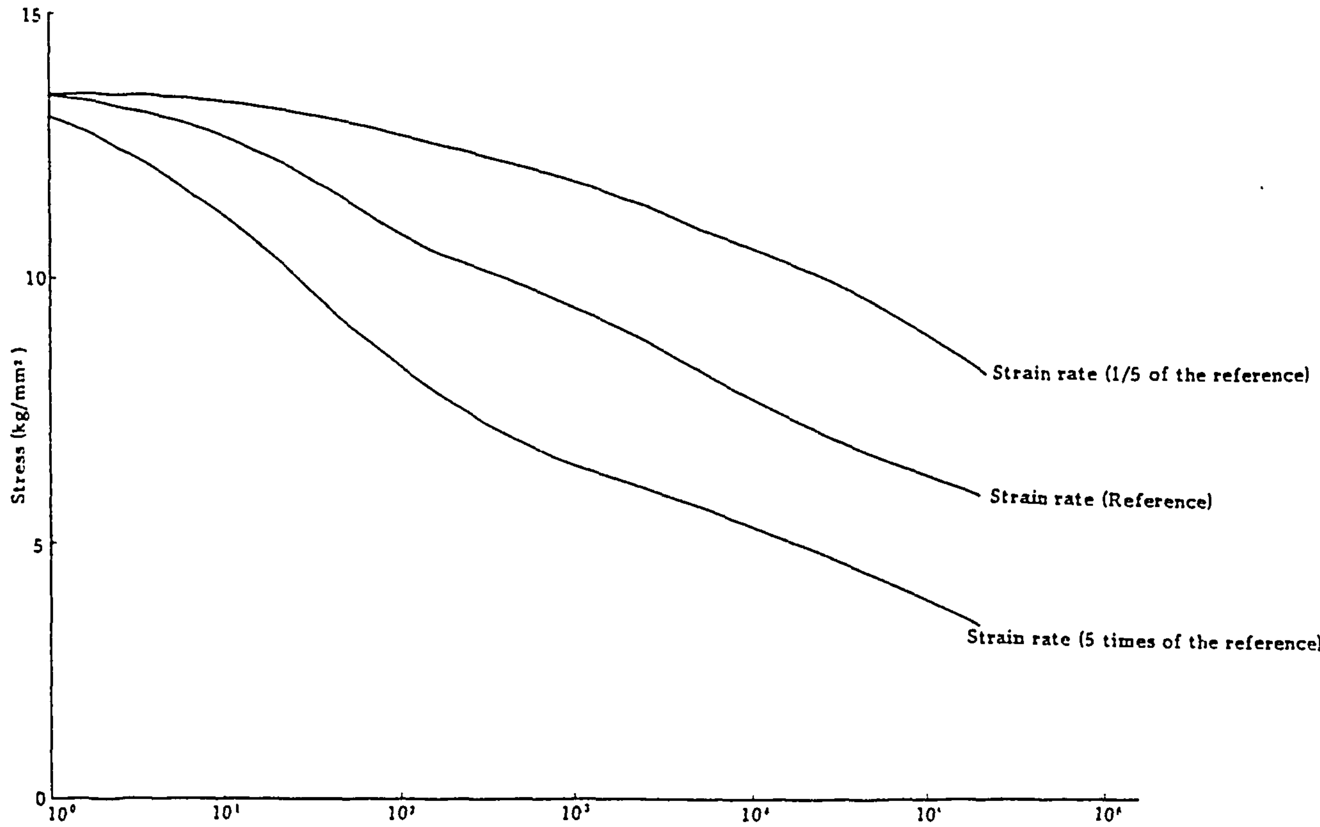

Fig. 2 Relaxation Curve (304SS, 550°C)
(effect of strain rate)

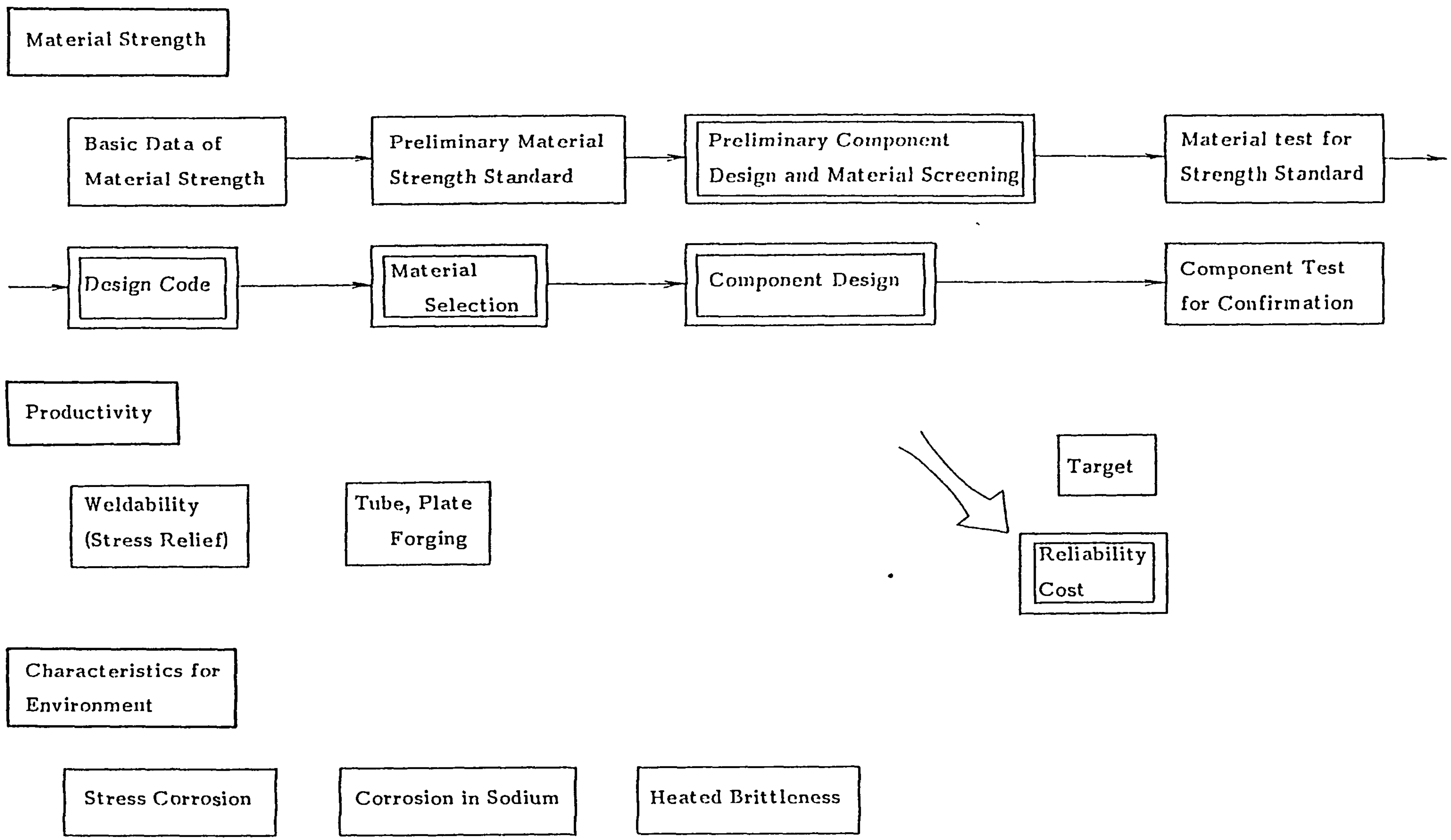

Fig. 3 Flow Diagram for Material Selection (Typical Example)