A Metallurgical Approach to Improved Cavitation-Erosion Resistance

R.H. Richman and W.P. McNaughton

Although cavitation erosion in hydraulic systems is an old problem, the damage mechanism that culminates in material loss was not known with certainty until recently. An investigation is described that aimed at clarifying the damage mechanism in cavitation erosion and applying that knowledge to make hydraulic equipment more resistant to cavitation. Strong correlations were established between cyclic deformation (fatigue) parameters and cavitation-erosion rates. This identification facilitated the search for more resistant materials. Finite element modeling confirmed that localized impacts on metal surfaces produce fatiguelike deformations and damage accumulation. Among available materials, near-equiatomic alloys of nickel and titanium are anomalously resistant to low-cycle fatigue and thus should be very resistant to cavitation erosion. Experiments confirmed the expected erosion resistance. Building large machines entirely out of NiTi is impractical, however, and a way of selectively cladding common constructional materials is required. Because NiTi has not been fusion welded successfully to other alloys, explosive bonding of thin NiTi plates to structural steel was investigated. Excellent welds were achieved, and the erosion resistance of the resulting clads has been demonstrated. Comparisons are made to other erosion processes and to other erosion-resistant materials, and some applications to hydraulic devices are suggested.

Keywords erosion cavitation, explosive bonding, fatigue, NiTi

1. Introduction

Material removal by erosion imposes limitations on technologies in many industries. Although recent developments in materials design and fabrication have opened abundant opportunities for tailoring materials to specific applications, mitigation of erosion damage through materials improvements and surface treatments has been hampered because the damage mechanism in cavitation erosion was unknown and thus it has not been possible to specify the materials properties that ensure good erosion resistance.

Machines subject to cavitation erosion (and closely related liquid-droplet erosion) include boiler feed pumps, valves, recirculation pumps in pressurized-water reactor (PWR) systems, hydroturbine runners and guide vanes, last-stage blades in steam turbines, and ship propellers. Although proper design is a necessary condition for long lives of equipment exposed to cavitation, it is often insufficient. For example, good design can ensure that cavitation does not occur in hydroelectric turbines during operation at full load, but such units may be run at reduced load for a significant portion of their lifetimes owing to the demands imposed by remotely initiated generation dispatch decisions. Consequently, there is a significant premium on improved cavitation-erosion resistance to extend equipment life and to decrease repair costs from the cavitation exposures that occur while operating in those hydraulically nonoptimal regimes.

Many attempts were made over the years to find a material property or combination of properties that correlates with measured cavitation-erosion rates, but without much success (Ref 1). There was, however, agreement that material removal in multiple-impact situations (cavitation erosion, liquid-droplet erosion, and most instances of solid-particle erosion) is not a result of single impulses or impacts. That is, damage accumulates over thousands of impacts before a particle is dislodged (Ref 2, 3). Several investigators had attributed the failure mode specifically to fatigue (Ref 4-6), and evidence of fatigue can be deduced from experiments (Ref 7-10).

The basis for the present investigation was that if cavitation erosion is fatiguelike, then the factors contributing to fatigue resistance of materials (Ref 11, 12) should offer clear direction for achieving improved cavitation-erosion resistance.

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2. Overview of the Approach

As shown in Fig. 1, the investigation has thus far consisted of three stages:

- Statistical analysis and early modeling studies (identification of the damage mechanism by correlation, then finite element modeling to confirm that identification)
- Laboratory testing of candidate materials (survey of candidates with appropriate properties and choice of a prime candidate)
- Moving to field application (explosive welding of NiTi to steel, exploration of other cladding methods, and further modeling studies)

The purpose of this paper is to describe the sequence of actions and their results.

3. Identification of Fatigue as the Damage Mechanism in Cavitation and Liquid-Droplet Erosion

3.1 *Cavitation Erosion*

If erosion damage accumulates by fatigue, there should be a clear relationship between erosion behavior and cyclic deformation parameters. Fatigue behavior is characterized quantitatively by analyzing the responses of metals and alloys to cycling between strain limits (Ref 13). The ensuing strain-life relation is the sum of elastic and plastic strain resistance, as shown in Fig. 2 where the following parameters are illustrated: the fatigue strength coefficient (σ_f'), the fatigue ductility coefficient (ε_f'), the fatigue strength exponent (*b*), and the fatigue ductility exponent (*c*). Also central to fatigue behavior is the cyclic strain-hardening exponent (*n*′), which Morrow (Ref 13) showed is equal to *b*/*c*.

Strong correlations were demonstrated between cyclic deformation properties and damage rates in cavitation erosion (Ref 14, 15). The main determinant of erosion resistance is the fatigue strength coefficient, (σ_f'), which is a measure of cyclic *stress* resistance. Material removal rates correlate best with the product of ($\sigma_f' \cdot n'$), in which *n*′ reflects the cyclic *strain* resistance. Figures 3 and 4 illustrate the nature of the correlations obtained. Note that the results are general over a wide range of metals and alloys. Furthermore, this result explains why previous attempts to correlate cavitation erosion and liquid-droplet erosion behavior with a simple mechanical or materials property were unsuccessful. Because σ_f' is strongly mediated by cyclic strain hardening, erosion behavior is not simply related to any monotonic property such as true fracture stress or ultimate tensile stress.

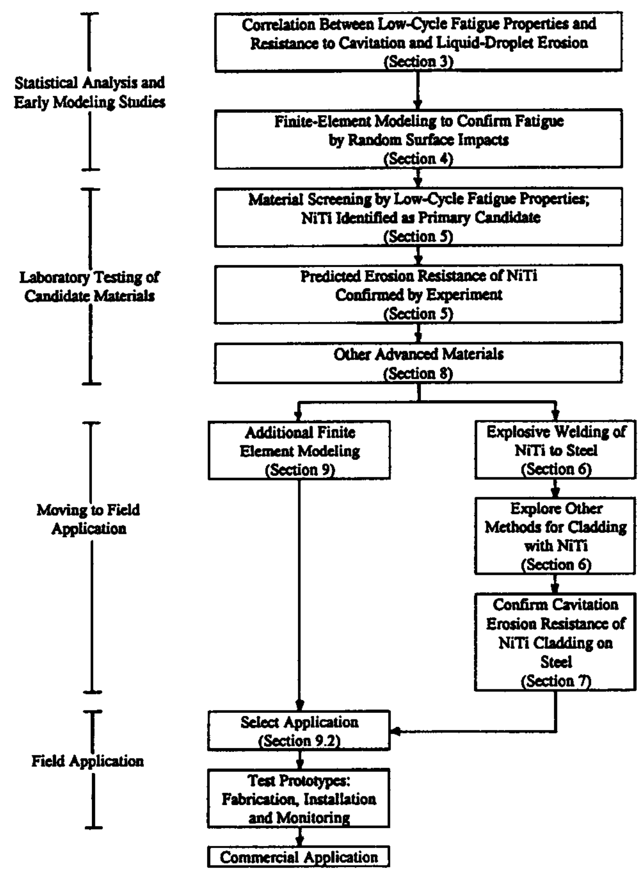


Fig. 1 Schematic of a metallurgical approach to cavitation-erosion resistance

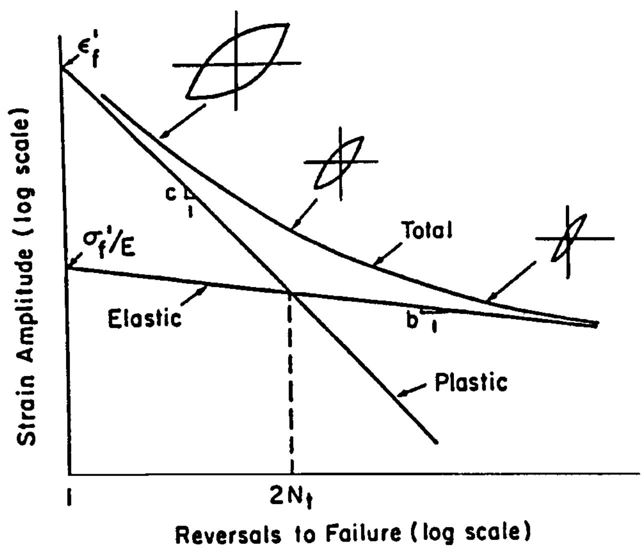


Fig. 2 Relationships of fatigue life to elastic, plastic, and total strain amplitudes; the shapes of the stress (vertical)-strain (horizontal) hysteresis loops are shown for three typical points on the strain-life curve

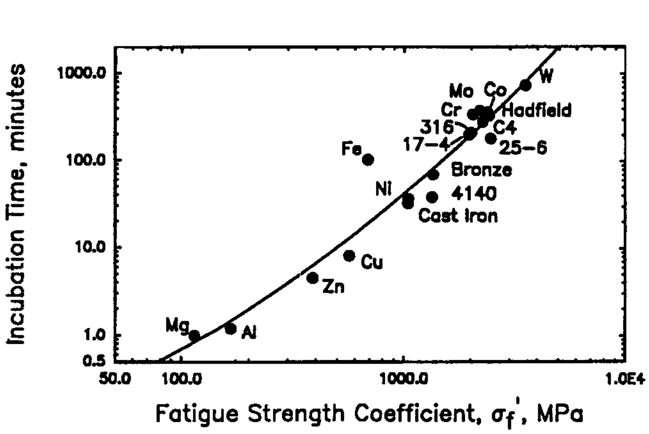


Fig. 3 Dependence of incubation time for cavitation erosion on fatigue strength coefficient

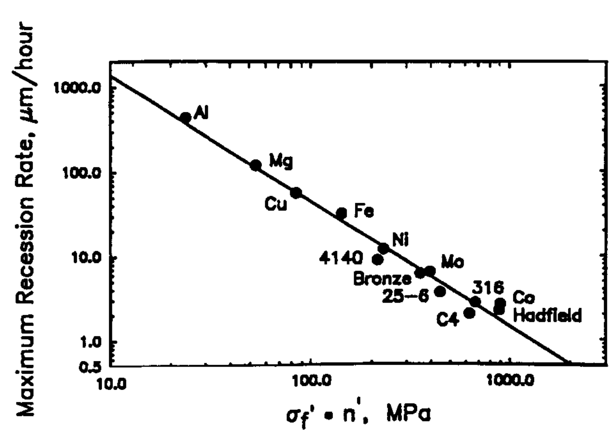


Fig. 4 Dependence of maximum erosion rate in cavitation erosion on the combined parameter $\sigma_f' \cdot n'$

3.2 *Liquid-Droplet Erosion*

Similar statistical correlations were sought using published compilations of liquid-droplet erosion behavior (Ref 15). Although consistent data sets were somewhat harder to find, Fig. 5 shows that either σ_f' or $\sigma_f' \cdot n'$ describes erosion by liquid droplets fairly well.

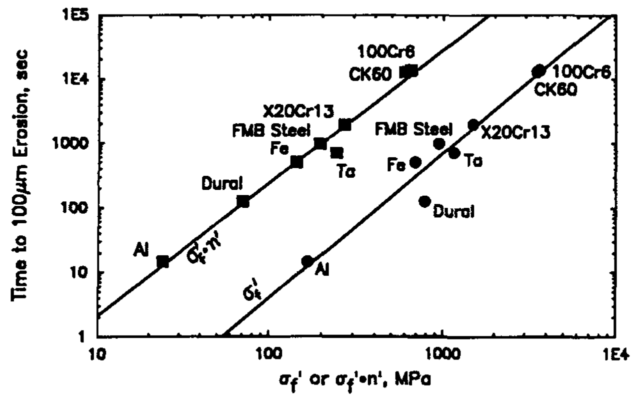


Fig. 5 Correlations between σ_f' or $\sigma_f' \cdot n'$ and material removal rates by water-droplet impingement

4. Finite Element Modeling to Confirm Cyclic Deformation from Random Impacts

In parallel with the correlation work, the erosion by multiple impacts was simulated with a conceptually simple model of repeated indentation on an elastic-plastic material (Ref 16) (Fig. 6). Application of a model for materials that follow a kinematic hardening law reproduces the stress-strain responses characteristic of fatigue processes: stress and strain reversals, hysteresis loops, and strong history effects. Although the model was extended to fifty randomly located load/unload cycles, the simpler case of alternating indentations at two locations provides a much clearer illustration of damage development during erosion. Figure 7 shows the maximum shear stress-strain curves

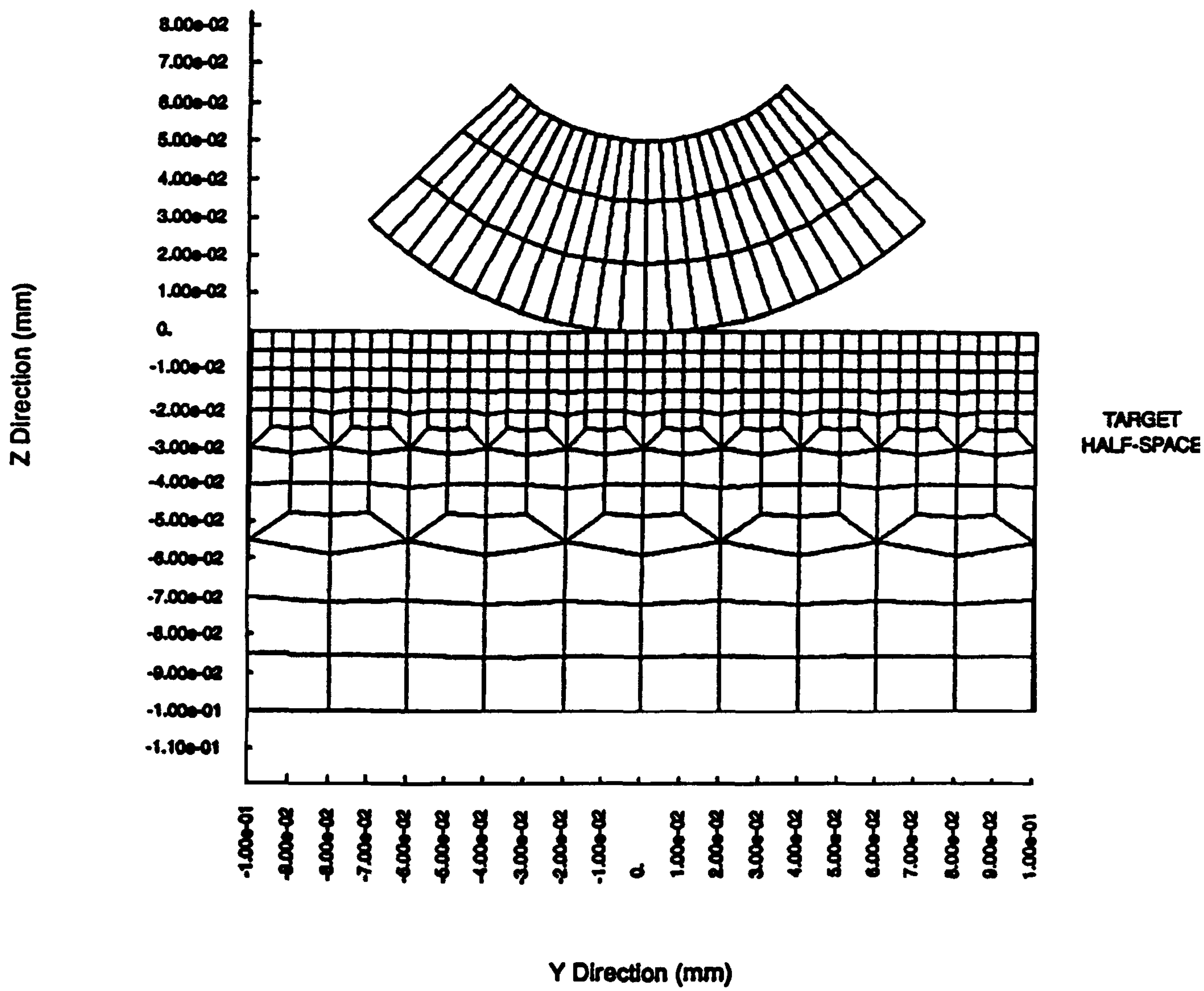


Fig. 6 Finite-element mesh of the indenter and half-space

for a representative model element. A quasi-static load/unload process simulated a load/unload cycle near to the element (the large hysteresis loops) and then one removed from the element (the smaller loops). After the initial shakedown to stable behavior, the ensuing hysteresis loops (a measure of damage accumulation) take on characteristic shapes and sizes that depend sensitively on the intensity of the load and on the location of the load relative to a reference element in the half-space (Ref 16).

5. Emergence of NiTi as the Prime Candidate for Erosion Resistance

Near-equiatomic NiTi (nickel-titanium) alloys exhibit anomalously high resistance to low-cycle fatigue (Ref 17, 18).

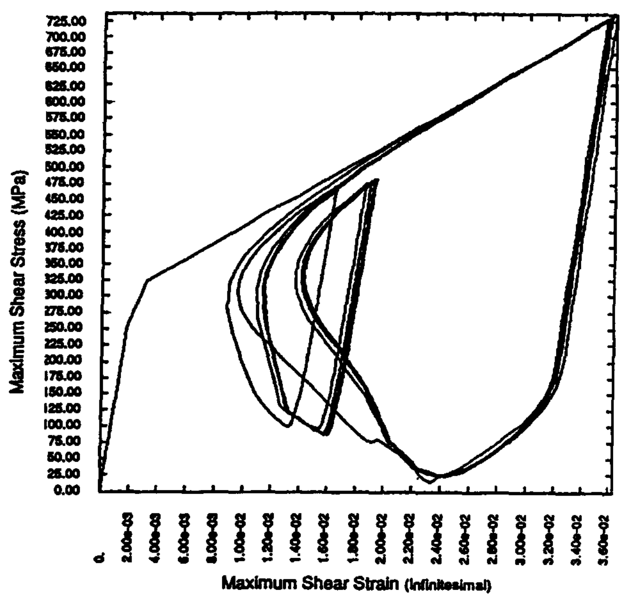


Fig. 7 Shear stress-shear strain curves for a representative element: twelve alternating indentations on type 304 stainless steel at nodes 18 and 21

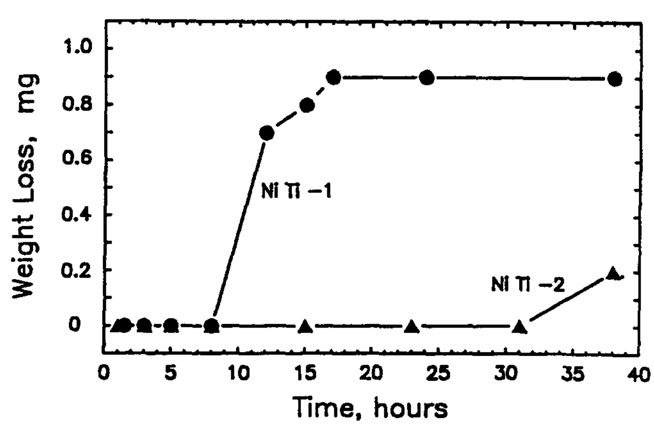


Fig. 8 Cumulative weight loss with time in vibratory cavitation for two NiTi alloys

It would be expected from the correlations previously developed that their resistance to cavitation erosion would likewise be high. There are two very different forms of NiTi: a relatively soft martensitic phase (*B*19′ structure) with a low elastic modulus and a stronger, stiffer, austenitic phase that is atomically ordered (*B*2 structure).

The martensite responds to stress by twin-boundary motions within martensite crystals and by preferential growth of some martensite variants at the expense of others (Ref 19). In contrast, deformation of austenite at temperatures near the transformation temperature occurs by formation of martensite, which reverts to austenite when the stress is removed (superelastic behavior) (Ref 20).

On the basis of their low-cycle fatigue properties, either superelastic or martensitic NiTi should be resistant to cavitation erosion, and both structures were tested. Table 1 summarizes the nominal alloy compositions, structures, and transformation temperatures. Flat specimens were metallographically polished and exposed to cavitation (with specimen stationary) in a device similar to that described by Preece and Hansson (Ref 2). Cavitation was induced by a tip vibrating at 20 kHz, with amplitude ±25 μm, located at 0.5 mm from the specimen.

Both forms of annealed NiTi turned out to be remarkably resistant to cavitation erosion (Ref 21). Exposure time had to be extended to at least 38 h (in contrast to the usual 12 h or fewer) in order to obtain measurable weight losses, as shown in Fig. 8. The weight loss of NiTi-1 between 10 and 18 h, followed by a zero erosion rate, is unusual and may reflect a peculiarity of the particular specimen. In any case, weight loss was very low for both forms of NiTi. The issue of which form is superior is not yet settled, as is discussed later in this paper.

6. Explosive Cladding of Steel with NiTi

Building large industrial components entirely of NiTi to take advantage of the superior cavitation erosion properties would be prohibitively expensive, and it would be difficult to

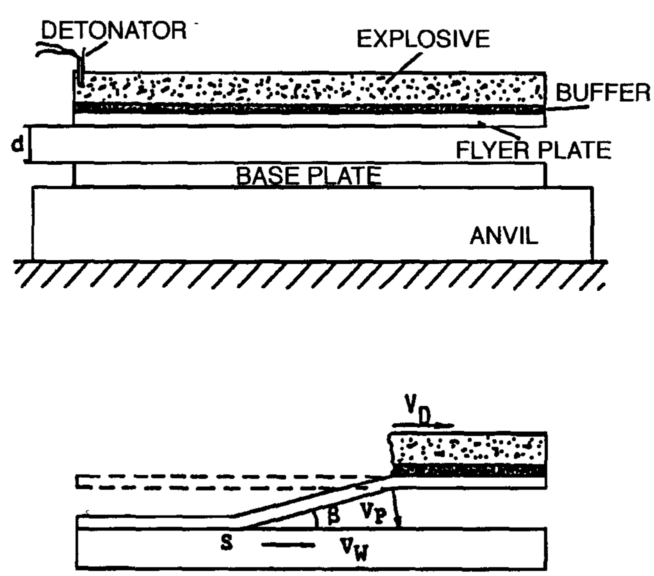


Fig. 9 Parallel explosive welding arrangement

maintain the required properties in thick sections. The obvious route to practical use of NiTi is to overlay an inexpensive material such as steel with NiTi in locations where erosion by cavitation or liquid droplets is a threat. The method of joining is a primary concern. Conventional fusion welding is not an option with NiTi because brittle phases are formed in the fusion zone. Likewise, NiTi coatings deposited by thermal spray methods in thicknesses on the order of 1 mm have, so far, neither the requisite adherence to steel nor adequate structural integrity to withstand severe cavitation (Ref 22).

With explosive welding, excellent bonds were achieved between thin plates of NiTi and thicker sections of structural steel. The process, illustrated schematically in Fig. 9, involves the high-velocity impact between two or more metal plates. Because explosive welding is a solid-state process, unwanted reactions between the metals themselves, reactions between the metals and the environment, formation of as-cast microstructure, and formation of a heat-affected zone are all avoided.

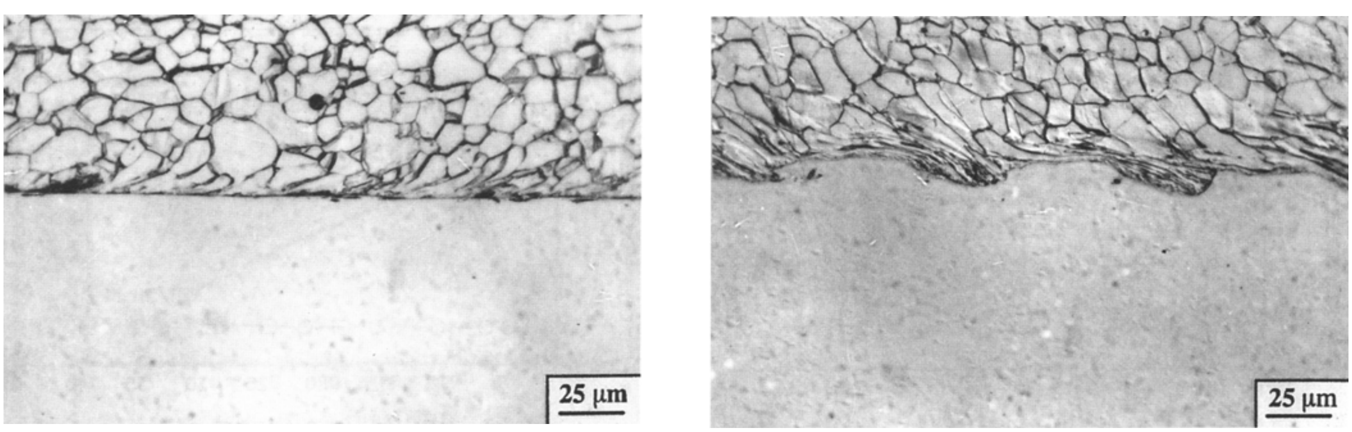
The explosive welding parameters of standoff distance and frame height (amount of explosive) were systematically varied (Ref 23). Detonation velocities of 2000 to 2200 m/s and flyer-plate velocities of 385 to 440 m/s resulted in welds with flat interfaces at the lower velocities (Fig. 10a) or wavy morphology at the higher velocities (Fig. 10b). Tensile lap-shear tests attested to the integrity of the resulting bonds (Table 2). The three failures at the interface between martensitic NiTi and low-carbon steel suggest that the explosive welding parameters had not been optimized.

Table 1 Alloy compositions, structures, and transformation temperatures

Designation	Composition, wt% Ni	Composition, wt% Ti	Composition, at.% Ni	Composition, at.% Ti	Structure	Martensite start (M_s) temperature, °C
NiTi-1	55.07	44.93	50	50	Martensite (*B*19′)	80
NiTi-2	55.76	44.24	50.7	49.3	Ordered bcc (*B*2)	–25

Table 2 Tensile lap-shear tests on explosively welded NiTi/low-carbon steel

NiTi form and condition	Bonded zone morphology	Stress at interface, MPa	Stress at interface, ksi	Failure location
Austenite, as-welded	Straight	246	35.7	Steel
	Straight	248	35.9	Steel
	Wavy	270	39.2	NiTi
	Wavy	354	51.4	NiTi
Austenite, welded and PWHT at 500 °C	Straight	387	56.2	Interface
	Straight	318	46.1	NiTi
	Wavy	280	40.6	NiTi
	Wavy	250	36.2	NiTi
Martensite, as-welded	Wavy	189	27.4	Interface
	Wavy	181	26.2	Interface
	Wavy	189	27.4	Interface



(a) (b)

Fig. 10 Micrographs of bond interfaces between NiTi and steel. (a) Straight morphology. (b) Wavy morphology

7. Cavitation Erosion Resistance of Explosively Welded NiTi

After explosive welding, the hardness of austenitic NiTi had increased from an average of 285 HV to an average of 348 HV and x-ray diffraction spectra contained some low-intensity peaks associated with the martensitic phase. Both observations indicate some residual damage in the austenite as a consequence of explosive welding, which was reflected in substantially reduced resistance to cavitation erosion (Fig. 11). The effects of two postweld treatments (PWHT) are also shown in Fig. 11; 700 °C for 15 min further degraded cavitation resistance slightly, whereas 500 °C for 15 min restored most of the lost resistance (Ref 24).

In contrast, explosive welding of martensitic NiTi caused only a small hardness increase (from 235 to 263 HV) that did not seem to affect the resistance to damage by cavitation erosion; if anything, the weight loss of as-welded martensite up to 35 h exposure is lower than that of unwelded (annealed) NiTi (Fig. 12). Furthermore, PWHT at 500 °C increased the weight loss early in cavitation exposure (Ref 24). Notice, however, that the slope of the weight loss versus time curve (i.e., the erosion rate) at long times is lower for the postweld heat treated martensitic NiTi than for the as-welded condition.

A simple comparison of the erosion behaviors of the most resistant austenitic and martensitic NiTi explosively welded to steel is given in Fig. 13. There does not seem to be a statistically significant difference in cavitation erosion resistance between the as-welded martensitic NiTi and austenitic NiTi welded + PWHT (500 °C).

8. Comparison to Other Erosion-Resistant Materials

Although the balance of this paper focuses on NiTi, a brief mention is made here of some conventional and "advanced" materials for which cavitation-erosion behavior has been measured. As shown in Fig. 14, NiTi cladding on low-carbon steel is much more resistant to cavitation than the CA6NM (cast martensitic), type 304L (wrought austenitic), or FER-255 (duplex) stainless steels that are commonly used in hydraulic machinery. Recently, there has been considerable interest in diamondlike coatings (DLC) (Ref 25) and in nickel or iron alu-

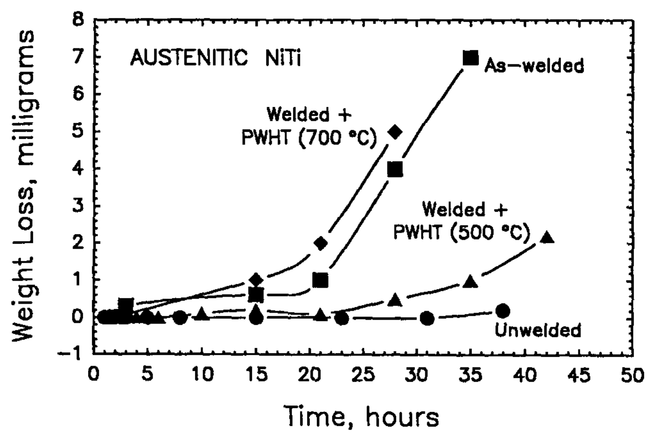


Fig. 11 Cumulative weight loss in vibratory cavitation for austenitic NiTi: unwelded (annealed), as welded, and welded plus PWHT

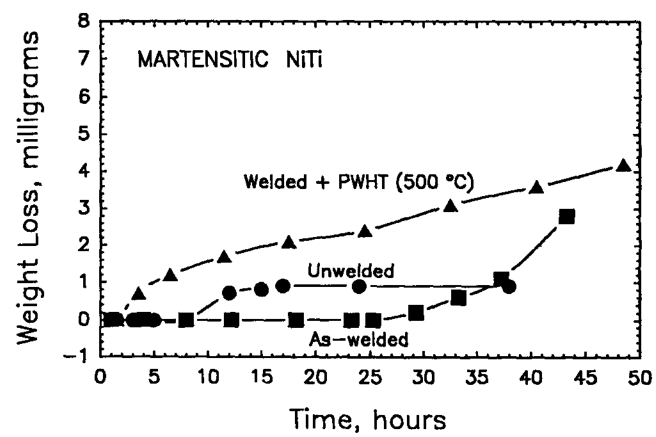


Fig. 12 Cumulative weight loss in vibratory cavitation for martensitic NiTi: unwelded (annealed), as welded, and welded plus PWHT

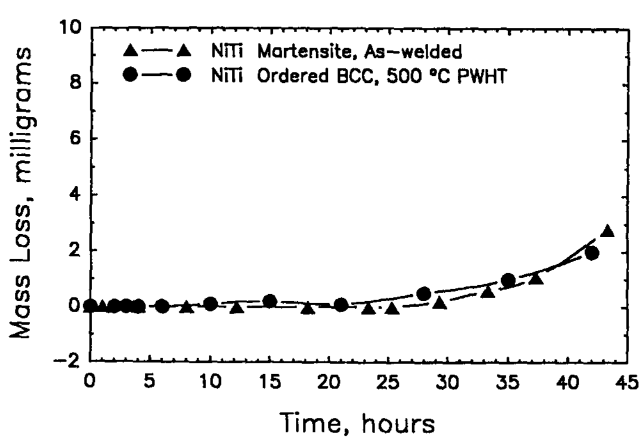


Fig. 13 Cavitation erosion of austenitic (PWHT at 500 °C) and martensitic (as-welded) NiTi explosively welded to steel

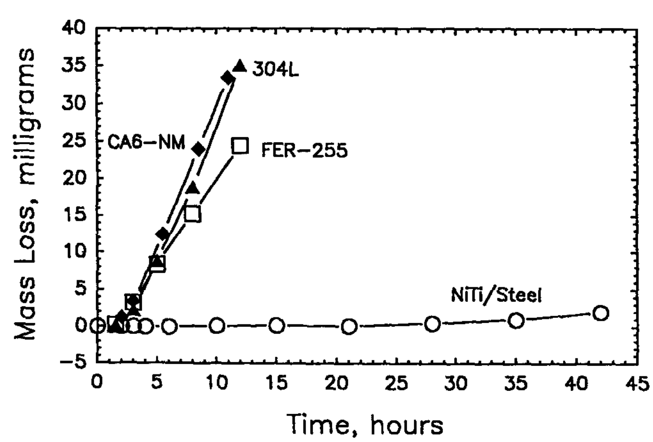


Fig. 14 Comparison among CA6NM, type 304L, FER-255, and NiTi/steel in vibratory cavitation

minides (Ref 26) for erosion protection. Our vibratory cavitation tests have confirmed the superiority of both of these developments over "standard" materials; however, as seen in Fig. 15 and 16, neither the DLC nor the aluminides provided to us were as resistant as NiTi.

Cobalt-base alloys such as Stellite 6 (ST-6) and Stellite 21 (ST-21) are well known for their resistance to cavitation, and they have been used successfully as weld overlays to protect hydroturbines (Ref 27). However, they are costly and they are not well suited for use in nuclear-generating applications owing to long-lived radioactivity retained by cobalt in wear or erosion debris. Hydro Quebec developed a less costly series of cobalt-containing stainless steels (IRECA alloys) that are also intended as weld overlays for protection against cavitation erosion (Ref 27).

Figure 17 summarizes the performance of three "standard" and four very erosion-resistant alloys tested in vibratory cavitation. Expressing erosion susceptibility as relative to that of type 304 stainless steel alloys allows intercomparison among several investigations (Ref 27-29). Considering only steady-state erosion rates, NiTi/steel appears to be about three times more resistant to material removal than the next-best alloy. In fact, explosively welded NiTi/steel tandems are more erosion resistant than any other material that we have tested in this way.

9. Current Activities

It has been established that there are measurable materials properties (strain-based fatigue parameters) that can be used to predict the propensity of a material to erode by cavitation. The accumulation of damage by cyclic impact was confirmed by finite element analyses. The knowledge thus gained has been used to find promising innovative materials for industrial applications where erosion resistance is a primary design goal. NiTi has been found to offer such potential, and a program to find means to attach thin, resistant layers to inexpensive substrates of constructional materials has successfully demonstrated that explosive welding is an appropriate way to achieve such a tandem. The tandem has excellent erosion properties. Our current efforts focus on two primary activities: additional finite element modeling and refinements of the fabrication process to allow field prototype testing.

9.1 *Finite Element Modeling*

The following key questions should be answerable by modeling:

- Does a dynamic material-response model correct the deficiencies of the quasi-static model, and does it improve our understanding of damage accumulation by erosive processes?
- How should damage be accounted impact-by-impact so that erosion rates can be predicted from first principles?
- What is the optimal thickness of any given kind of surface layer in order to obtain the most effective protection against erosion?

Of these issues, the first two are currently being addressed, although our current modeling studies are oriented more toward solid particle impact than toward cavitation bubble collapse. After a satisfactory dynamic model is in hand, we will explore the question of optimal protective-layer thickness.

9.2 *Application and Prototype Testing*

The explosively welded NiTi/steel tandem offers significant opportunities for a variety of applications. As we focus on picking early applications for prototype testing, potential stumbling blocks to field use continue to be considered.

For example, a likely approach would be to minimize material costs by conferring protection with NiTi only where it is needed, that is, in those areas where cavitation or liquid-droplet erosion is a threat. To this end, we have recently developed the capability to weld patches of NiTi in shallow pockets machined in the surfaces of structural steel plates so as to preserve hydraulic profiles. Experiments are currently underway to weld NiTi to martensitic stainless steel (types 410 and 422) with sharply curved profiles to simulate the leading edges of last-stage blades in steam turbines.

It may be possible eventually to bond patches in situ on large machine components. For the time being, however, we are focusing on shop-fabricated welds for applications in electric

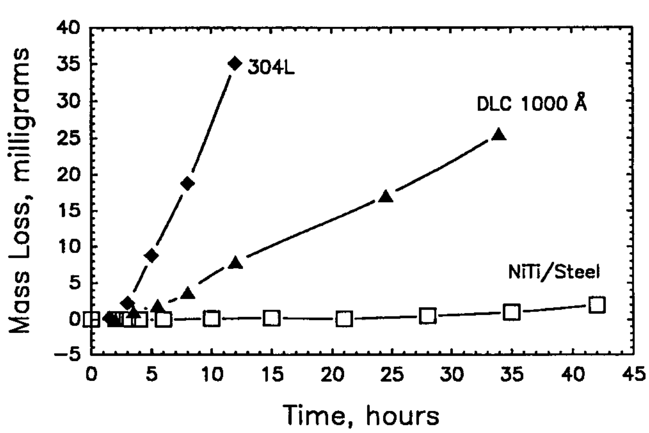


Fig. 15 Cavitation-erosion behavior of DLC (on type 304 stainless steel) compared to type 304L and NiTi/steel

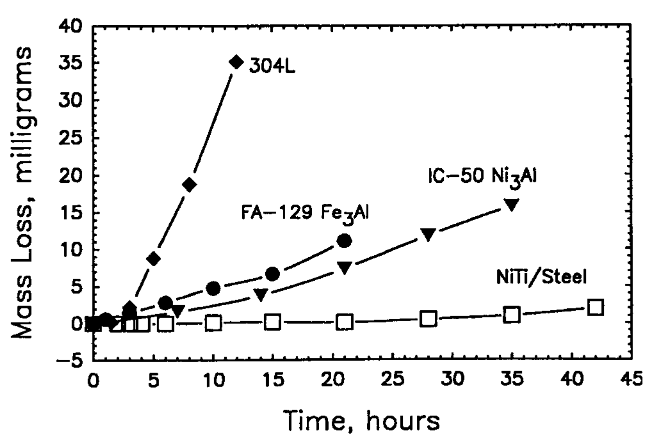


Fig. 16 Cavitation-erosion behavior of iron and nickel aluminides compared to type 304L stainless steel and NiTi/steel

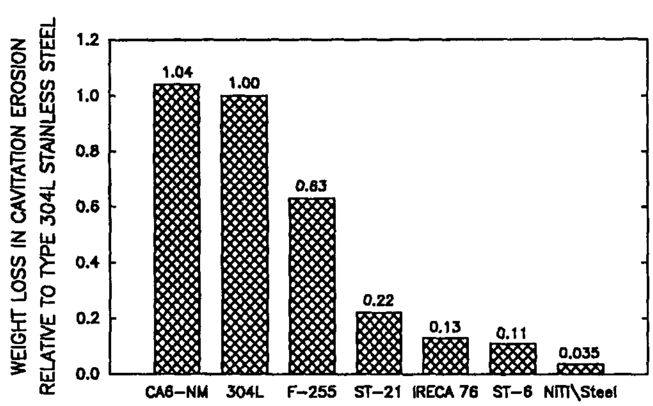


Fig. 17 Relative erosion rates in vibratory cavitation

power generation such as hydroturbine blades and vanes, pump impellers, removable valve seats, and erosion shields on last-stage blades in steam turbines.

10. Summary

It has been shown in this account that a long-standing problem, cavitation erosion, can be resolved by a logical sequence of activities: identification of the damage mechanism; confirmation of the damage mechanism; survey of candidate materials with properties appropriate to resist the identified damage; and conferring protection against cavitation erosion by cladding an inexpensive material with a thin layer of a highly resistant one. A key step in the investigation was identification of fatigue as the main damage mechanism of cavitation erosion. Confirmation of the mechanism by finite element modeling then enabled a rational search for materials with the requisite fatigue properties: high fatigue strength coefficient combined with a high cyclic strain-hardening exponent. Near-equiatomic alloys of nickel and titanium were found to possess those properties, and indeed they are very resistant to cavitation erosion. However, NiTi alloys cannot be fabricated in thick sections and they are costly. Accordingly, methods for selectively cladding steel with NiTi by explosive welding were developed. Explosively bonded NiTi/steel composites appear to have promise for a variety of applications in which protection against cavitation erosion is desired.

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