Office de la Propriété Intellectuelle du Canada
Un organisme d'Industrie Canada

Canadian Intellectual Property Office
An agency of Industry Canada

CA 2207354 C 2004/09/28

(11)(21) 2 207 354

(12) BREVET CANADIEN
CANADIAN PATENT

(13) C

(22) Date de dépôt/Filing Date: 1997/06/09

(41) Mise à la disp. pub./Open to Public Insp.: 1998/04/07

(45) Date de délivrance/Issue Date: 2004/09/28

(30) Priorité/Priority: 1996/10/07 (732,644) US

(51) Cl.Int.^{6}/Int.Cl.^{6} G01N 3/48

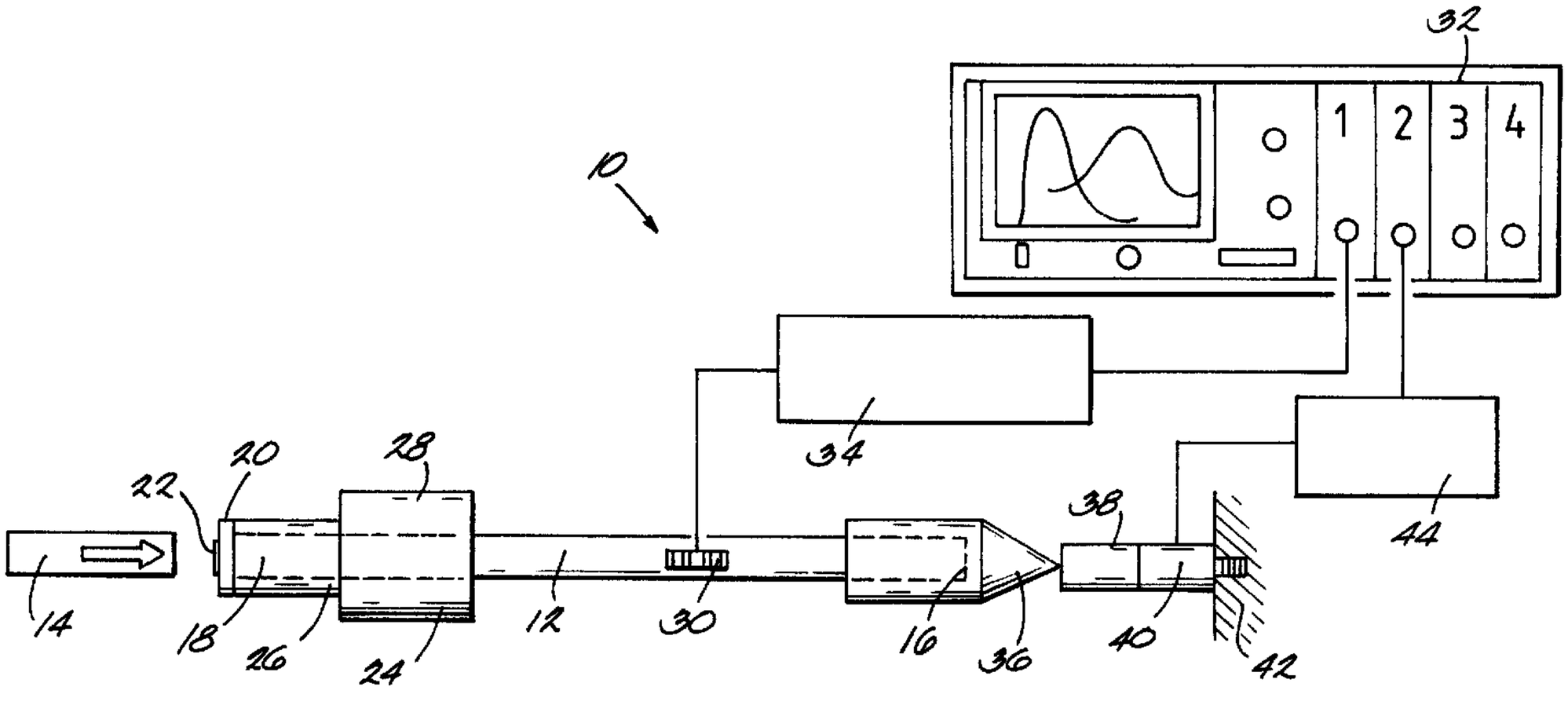
(72) Inventeurs/Inventors:
SUBHASH, GHATU, US;
CHANDRA, ABHIJIT, US;
KOEPPEL, BRIAN J., US

(73) Propriétaire/Owner:
BOARD OF CONTROL OF MICHIGAN TECHNOLOGICAL UNIVERSITY, US

(74) Agent: MACRAE & CO.

(54) Titre : APPAREIL ET METHODE PERMETTANT DE DETERMINER L'INDICE DE DURETE PAR PENETRATION DYNAMIQUE DES MATERIAUX

(54) Title: APPARATUS AND METHOD FOR DETERMINING THE DYNAMIC INDENTATION HARDNESS OF MATERIALS



(57) Abrégé/Abstract:
An apparatus and method for determining dynamic indentation hardness values of a material using a propagating stress wave to make an indentation in the material. The invention provides such values without any prior knowledge of the material properties and enables the dynamic indentation hardness values to be directly compared to static indentation hardness values for the material.

ABSTRACT

An apparatus and method for determining dynamic indentation hardness values of a material using a propagating stress wave to make an indentation in the material. The invention provides such values without any prior knowledge of the material properties and enables the dynamic indentation hardness values to be directly compared to static indentation hardness values for the material.

APPARATUS AND METHOD FOR DETERMINING THE DYNAMIC INDENTATION HARDNESS OF MATERIALS

FIELD OF THE INVENTION

The invention relates to an apparatus and method for determining the indentation hardness of a material, and more particularly, to an apparatus and method for determining the dynamic indentation hardness of a material.

BACKGROUND OF THE INVENTION

Indentation hardness measurements have been used for several decades by machinists and researchers in various fields. Indentation hardness is a measure of a material's resistance to penetration or permanent deformation. Indentation hardness measurements have been used to successfully monitor the effectiveness of processes such as heat treating, casting, forming, and welding. For the machinist, indentation hardness may indicate a material's resistance to cutting.

Indentation hardness measurements are typically obtained by subjecting a material to a static indentation force with an indentor for typically 10-15 seconds, measuring the area of the indentation and then calculating the static indentation hardness using a test standard such as, for example, ASTM Test Method E92-82 for Vickers indenters which is set forth below:

$$\text{Vickers Hardness (HV)} = 2P\sin(\alpha/2)/d^2 = 1.8544P/d^2$$

wherein

P = load (kgf)

d = mean indentation diagonal (mm)

α = face angle of diamond = 136 degrees.

Although traditional static indentation hardness measurements provide insight into a material's behavior during a specific process, these measurements do not accurately and sufficiently represent a material's response during a dynamic event such as metal cutting or material removal during high speed machining. This

is because deformation mechanisms of most materials are known to be rate dependent. For example, increased yield and flow stresses at higher strain rates in the case of metals, and increased fracture stress in the case of ceramics are rate dependent effects. Therefore, static indentation measurements do not completely represent a material's behavior under dynamic events.

Many engineering applications involve dynamic loading conditions, e.g., machining, crashworthiness of automotive structures, impacts of space debris on space structures, and penetration resistance of armor materials. Existing hardness testers either measure only static indentation hardness or use a rebound technique to measure dynamic indentation hardness. The rebound technique to measure dynamic indentation hardness assumes constant yield pressure, neglects thermal effects and neglects sensitivity to indenter velocity therefore making the measurement of dynamic indentation hardness indirect and inaccurate. Moreover, the dynamic indentation hardness determined by the rebound technique cannot be compared to existing static indentation hardness values.

Accordingly, there is a need for an apparatus and method that can measure indentation hardness at strain rates similar to those encountered in actual dynamic processes. With the increasing use of composites in every realm of technology, there is a demand for quick and accurate determination of effective properties of these new materials. Dynamic indentation hardness measurements plays a key role in these activities.

SUMMARY OF THE INVENTION

The invention provides an apparatus and method for determining the dynamic indentation hardness of a material. The invention requires no prior knowledge of material characteristics which simplifies the measurement of dynamic indentation hardness. The

apparatus and method utilizes a propagating stress wave to make a single indentation in the material. By suitably positioning a load transducer, the dynamic indentation hardness of a material can be determined accurately. The apparatus and method is useful in evaluating dynamic material response under high rate loading processes such as material removal during machining, dynamic wear, impact loading, and dynamic fragmentation. The present invention is of significant value in assessing a material's ability to resist a specified dynamic load. Further, the invention can be used as a tool to quickly screen potential new materials to assess their suitability for dynamic applications. The obtained dynamic hardness can be directly compared to its static counterpart.

The invention provides for an apparatus and method for determining dynamic indentation hardness of a material using a propagating stress wave in a long slender bar. By mounting an indenter at one end and introducing a stress wave of suitable amplitude and duration at the other end, the invention delivers a single compressive stress pulse of required characteristics into the specimen material.

It is an object of the present invention to provide an improved apparatus and method for determining the indentation hardness of a material.

It is another object of the present invention to provide an apparatus and method for determining the dynamic indentation hardness of a material.

It is another object of the present invention to provide an apparatus and method for determining the dynamic indentation hardness of a material using loading pulses of less than one second.

It is another object of the present invention to provide an apparatus and method for determining indentation hardness having the load cell on the incident bar.

Other features and advantages of the invention will become apparent to those of ordinary skill in the art upon review of the following detailed description, claims, and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a side view of a first embodiment of the invention;

Fig. 2 is a partial side view of a second embodiment of the invention;

Figs. 3(a)-(e) are charts of load in Newtons v. mean indentation diagonals in mm. squared for tool steels;

Figs. 4(a)-(d) are charts of load in Newtons v. mean indentation diagonals in mm. squared for stainless steels;

Figs. 5(a)-(b) are charts of load in Newtons v. mean indentation diagonals in mm. squared for FCC materials;

Figs. 6(a)-(b) are charts of load in Newtons v. mean indentation diagonals in mm. squared for HCP materials;

Fig. 7 is a chart of load in Newtons v. mean indentation diagonals in mm. squared for D-2 Tool Steel for both placements of a load cell, front and back;

Fig. 8 is a chart entitled Change of Vickers Hardness under Dynamic Loading; and

Fig. 9 is a chart entitled Static and Dynamic Vickers Hardness.

Before one embodiment of the invention is explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments and of being practiced or being carried out in various ways. Also, it is to be understood that the phraseology and terminology used

herein is for the purpose of description and should not be regarded as limiting.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to Fig. 1, there is shown an apparatus 10 for measuring the dynamic indentation hardness of a material. Materials to be measured may include, for example, metals, ceramics, plastics and composites. The apparatus 10 includes a long slender incident bar 12 and a striker bar 14 both preferably fabricated of maraging steel. Preferably, the incident bar 12 is a modified Hopkinson pressure bar having a first end 16, a second end 18 and a flange 20 adjacent end 18. Optionally, the second end 18 can include a pulse shaper 22 that is mounted on flange 20 and is preferably copper. It should be noted however that a pulse shaper is not required for operation of the apparatus 10. The striker bar 14 is launched such as from a gas gun at a predetermined velocity toward the incident bar 12. The impact at the end 18 of the incident bar 12 generates a compressive stress pulse in the incident bar 12 which travels toward the end 16. The amplitude of the stress pulse depends upon the velocity of the striker bar 14. Stress pulse durations of 50-200 μs can be achieved by varying the length of the striker bar 14.

Preferably, the end 18 of the incident bar 12 is modified with a momentum trap 24 which includes a collar 26 and a mass 28. The momentum trap 24 is adapted to the configuration of the incident bar 12 and functions as described in Nemat-Nasser et al., Proc. R. Soc. Lond. A 435:371-391 (1991). The momentum trap 24 ensures that additional reflected tensile waves from

end 16 are trapped so that only a single compression stress pulse, the first stress pulse, reaches the end 16 of the incident bar 12. Through use of the pulse shaper 22 on the end 18 of the incident bar 12, loading and unloading rates can be customized.

Optionally, a strain gage 30 can be mounted on the incident bar 12 to confirm constant loading rates over a desired time duration. The strain gage 30 can be of various types such as, for example, model WK-06-250BF10C manufactured by M&M of Raleigh, North Carolina. The strain gage 30 captures the complete history of the stress pulse which is then recorded on a high speed multi-channel digital oscilloscope 32. A signal conditioner 34, such as a wheatstone bridge, is positioned between the strain gage 30 and the oscilloscope 32.

An indenter 36 is mounted on the end 16 of the incident bar 12. Preferably, the indenter 36 is a diamond indenter of the Vickers™ type such as a Vickers™ diamond indentor available from Leco Corp. of St. Joseph, Michigan. However, it should be noted that other types of indenters can be used with the present invention such as ball or cone indenters. In the first embodiment as shown in Fig. 1, the specimen 38 of material to be tested is mounted to a load transducer such load cell 40. The load cell 40 is mounted to a stationary surface 42. Preferably, the load cell 40 is a high natural frequency load cell of, for example, 200 kHz such as model 9213 from Kistler of Amherst, N.Y.

In another embodiment as shown in Fig. 2, the load cell 40 can be positioned on the incident bar 12 adjacent the indenter 36. The positioning of the load cell 40 is often

dependent upon space limitations where the apparatus 10 is to function. Although the positioning of the load cell 40 between the specimen 38 and the surface 42 yields a cleaner electronic signal, the indentation hardness results for a particular specimen 38 for both load cell positions are the same as demonstrated in Fig. 7 for D-2 Tool Steel.

The striker bar 14 impacting the incident bar 12

causes the indenter 36 to make a single indentation in the specimen 38. Upon indentation, the complete loading history of the specimen 38 is captured by load cell 40 in conjunction with an amplifier 44, such as a charge amplifier and recorded on the oscilloscope 32. The mean indentation diagonal of the specimen 38 is then determined either manually such as with the aid of a microscope or automatically measured such as with the aid of a laser measurement system.

With the load value from the recorded signal on the oscilloscope 32 and the mean indentation diagonal value, the dynamic hardness can be calculated manually or with the aid of a computer. For example, with the use of a Vickers indenter, the present invention conforms to the requirements of ASTM Test Method E92-82 for static Vickers hardness measurements and extends the concepts to the dynamic range. Accordingly, the dynamic indentation hardness value is calculated with the following formula:

Dynamic Vickers Hardness (DHV)= $2P\sin(\alpha/2)/d^2 = 1.8544P/d^2$ wherein

P = load (kgf)

d = mean indentation diagonal (mm)

α = face angle of diamond = 136 degrees.

It should be noted that with the use of other indenters, corresponding formulas, such as the ASTM Test Methods, are to be employed.

Optionally, a integrated circuit could be conventionally constructed and made part of a dynamic indentation hardness measurement device to automatically make the above calculation.

Using the apparatus 10 and method described above, the dynamic indentation values can be compared to the static indentation values of a particular material to determine the rate sensitive nature of the material. Static indentation hardness values can be obtained from conventional static indentation hardness testers such as model V-100-C2 available from Leco Corp. For some

materials such as metals, dynamic indentation hardness can be up to 30% greater than the static indentation hardness. See for example Figs. 3(a)-(e) pertaining to tool steels, Fig. 4(a)-(d) pertaining to stainless steels, Fig. 5(a)-(b) pertaining to FCC materials, Fig. 6(a)-(b) pertaining to HCP materials and Figs. 8 and 9.

The apparatus and method described above for measuring dynamic indentation hardness enables the following advantages.

Unlike present dynamic indentation testers, the present invention uses the same scale as conventional static indentation testers therefore making comparisons possible and accurate.

The present invention determines dynamic indentation hardness values many scales of magnitude quicker than the prior art wherein the loading period is typically 10-15 seconds. In contrast, the loading times for the present invention are on the order of 50-200μs.

Unlike other dynamic indentation testers, the present invention does not require any prior knowledge of the material to be tested.

Unlike other dynamic indentation testers, the present invention calculates a dynamic indentation hardness values that is load independent, which is a requirement of a material property.

The present invention enables all of the above advantages while maintaining simplicity of use.

We claim:

1. An apparatus for determining the dynamic indentation hardness of a material, said apparatus comprising:

an incident bar;

a momentum trap on said incident bar;

a striker bar that contacts said incident bar and propagates a stress wave of a predetermined amplitude and duration along said incident bar;

an indenter mounted on said incident bar adapted to contact the material; and

a load transducer positioned in contact with the material.

2. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 1 wherein said incident bar has a first end and a second end, wherein said momentum trap is mounted on said first end and wherein said striker bar contacts said momentum trap.

3. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 2 wherein said indenter is mounted on said second end of said incident bar.

4. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 1 wherein said incident bar is a long slender rod.

5. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 1 wherein said

load transducer is a load cell.

6. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 5 wherein said load cell is a high frequency load cell.

7. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 1 and further including an oscilloscope in communication with said load transducer.

8. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 1 and further including a computer in communication with said load transducer.

9. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 1 wherein said indenter is a Vickers type diamond indentor.

10. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 1 and further including a means for moving said striker bar into contact with said incident bar.

11. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 1 and further including an amplifier in communication with said load transducer.

12. An apparatus for determining the dynamic indentation hardness of a material, said apparatus comprising:

an incident bar having a first, impact end and a second end;

a striker bar that contacts said first, impact end of said incident bar and propagates a stress wave of a predetermined amplitude and duration along said incident bar;

an indenter mounted on said incident bar and spaced from said impact end, said indenter having a tip that is adapted to contact the material;

a load transducer positioned between said second end of said incident bar and said tip of said indenter; and

a momentum trapping means at said impact end of said incident bar for permitting only a single compression pulse to reach said indenter.

13. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 12 and further including a means for moving said striker bar into contact with said incident bar.

14. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 12 wherein said incident bar is a long slender rod.

15. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 12 wherein said load transducer is a load cell.

16. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 12 and further including an amplifier in communication with said load transducer.

17. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 12 and further including an oscilloscope in communication with said load transducer.

18. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 12 and further including a computer in communication with said load transducer.

19. An apparatus for determining the dynamic indentation hardness of a material as set forth in claim 12 wherein said indenter is a Vickers type diamond indentor.

20. A method for determining the dynamic indentation hardness of a specimen, said method comprising the steps:

mounting an indenter on an incident bar;

generating a stress pulse that travels along the incident bar such that the indenter contacts the specimen;

measuring the load applied to the specimen;

measuring the size of the indent caused by the indenter contacting the specimen; and

calculating the dynamic indentation hardness of the specimen using the measured load and size of the indentation.

21. A method for determining the dynamic indentation hardness of a specimen as set forth in claim 20 wherein said indenter is a Vickers diamond type indenter.

22. A method for determining the dynamic indentation hardness of a specimen as set forth in claim 21 wherein said step of calculating the dynamic indentation hardness of the specimen utilizes ASTM Test Method E92-82 formula for indentation hardness.

23. A method for determining the dynamic indentation hardness of a specimen as set forth in claim 20 and further including the step of comparing the calculated dynamic indentation hardness of said specimen to the static indentation hardness of said specimen.

24. A method for determining the dynamic indentation hardness of a specimen as set forth in claim 20 wherein the step of generating a stress pulse that travels along the incident bar includes the use of striker bar that contacts the incident bar.

25. A method for determining the dynamic indentation hardness of a specimen as set forth in claim 24 wherein the step of generating a stress pulse that travels along the incident bar includes the use of a momentum strap on the incident bar.

26. A method for determining the dynamic indentation

hardness of a specimen as set forth in claim 20 wherein the step of measuring the load applied to the specimen includes the use of a load transducer.

27. A method for determining the dynamic indentation hardness of a specimen as set forth in claim 26 wherein the load transducer is a high frequency load cell.

28. A method for determining the dynamic indentation hardness of a specimen as set forth in claim 20 wherein the step of calculating the dynamic indentation hardness utilizes an oscilloscope.

29. A method for determining the dynamic indentation hardness of a specimen as set forth in claim 20 wherein the step of calculating the dynamic indentation hardness of the specimen utilizes the ASTM Test Method formula that corresponds to the type of indenter mounted on the incident bar.

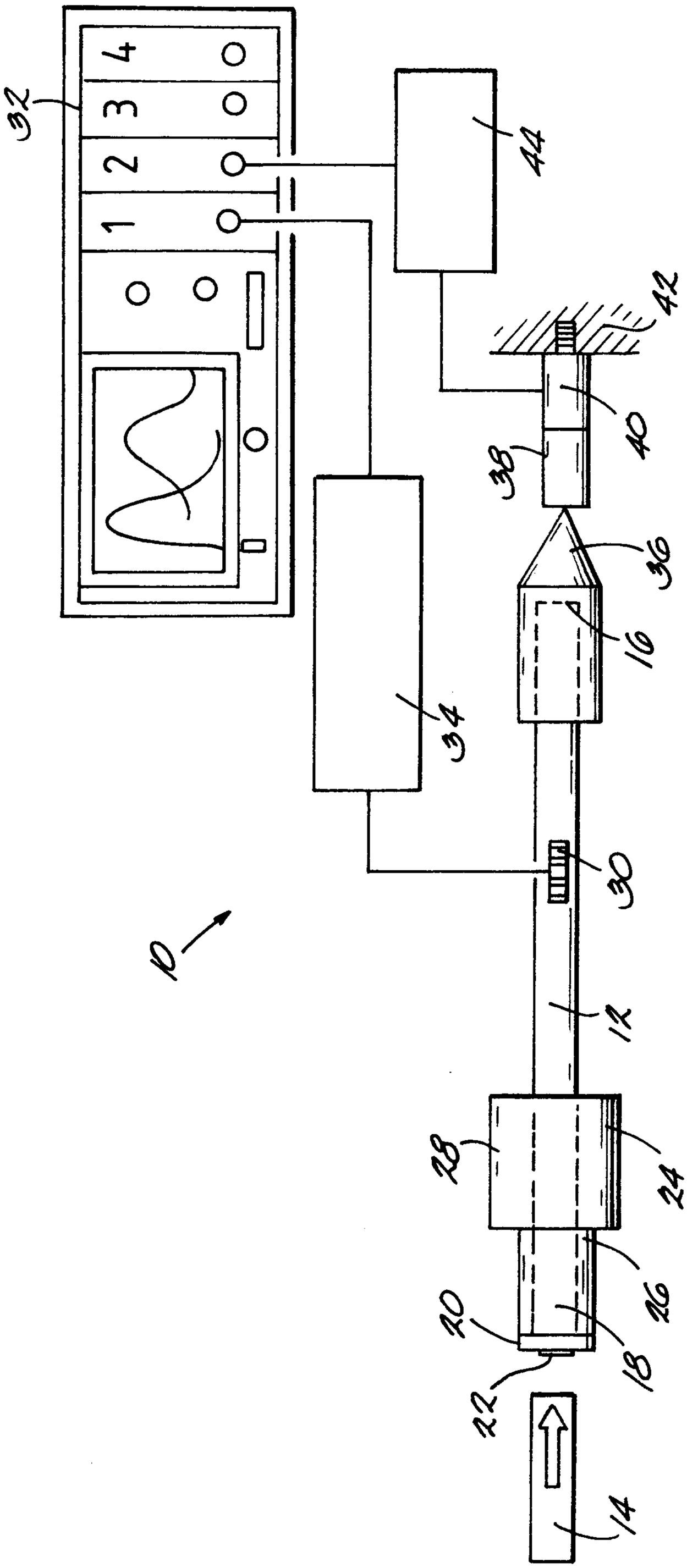


Fig. 1

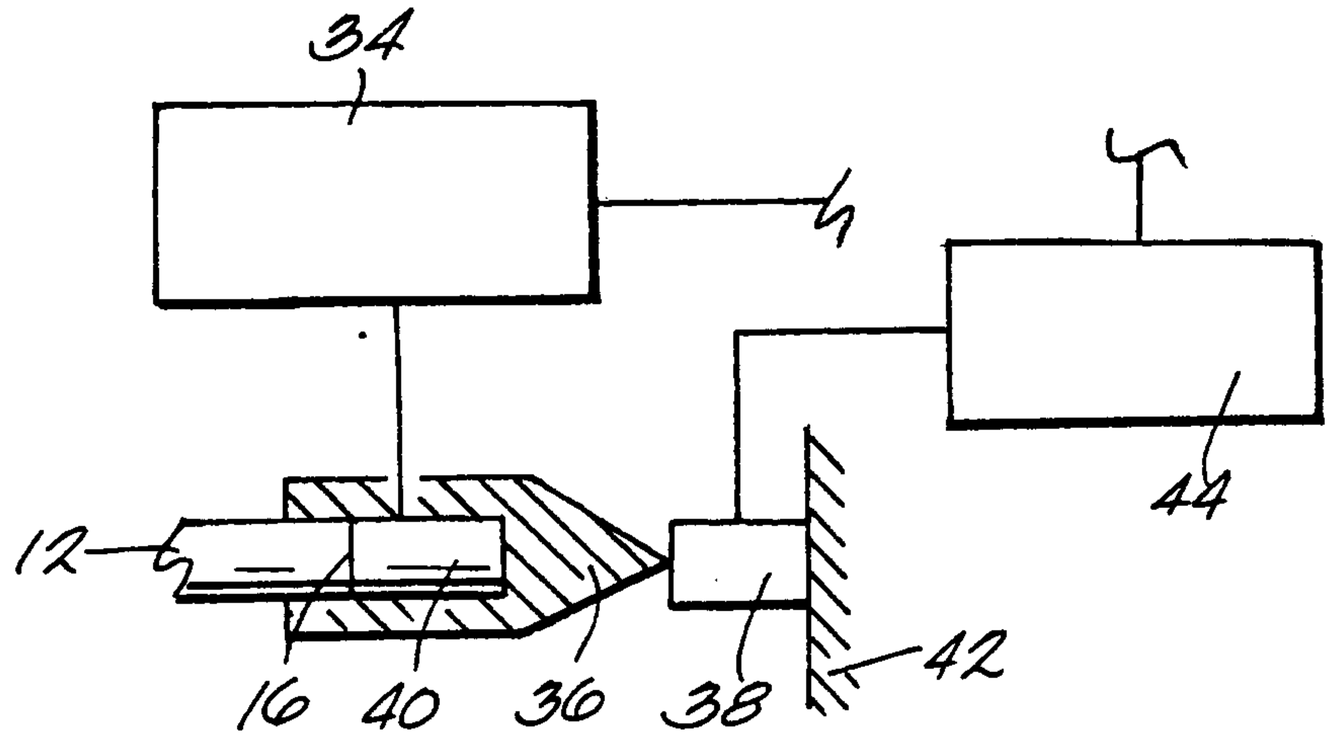


Fig. 2.

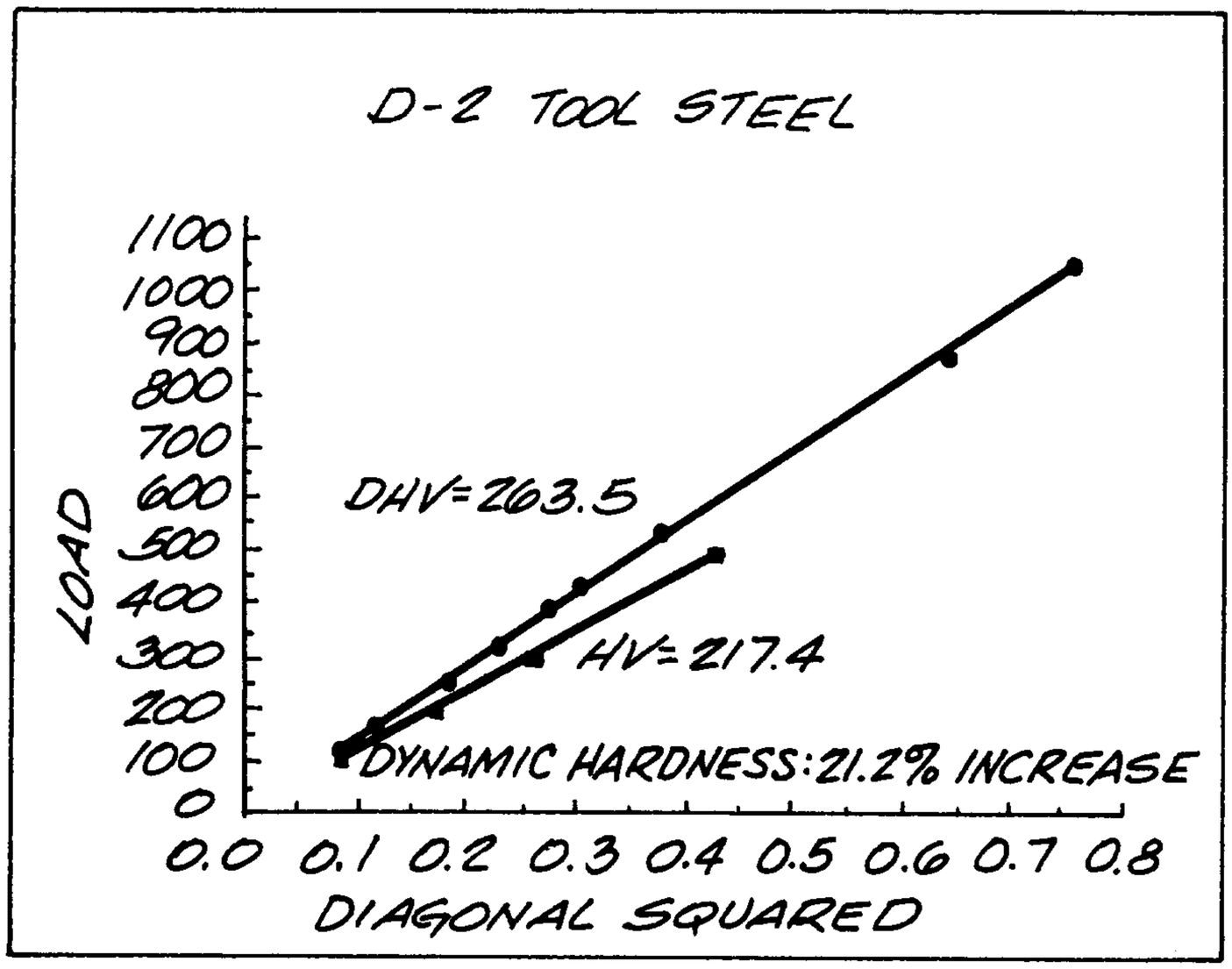

D-2 TOOL STEEL
LOAD
1100
1000
900
800
700
600
500
400
300
200
100
0
DHV=263.5
HV=217.4
DYNAMIC HARDNESS: 21.2% INCREASE
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
DIAGONAL SQUARED

Fig. 3a

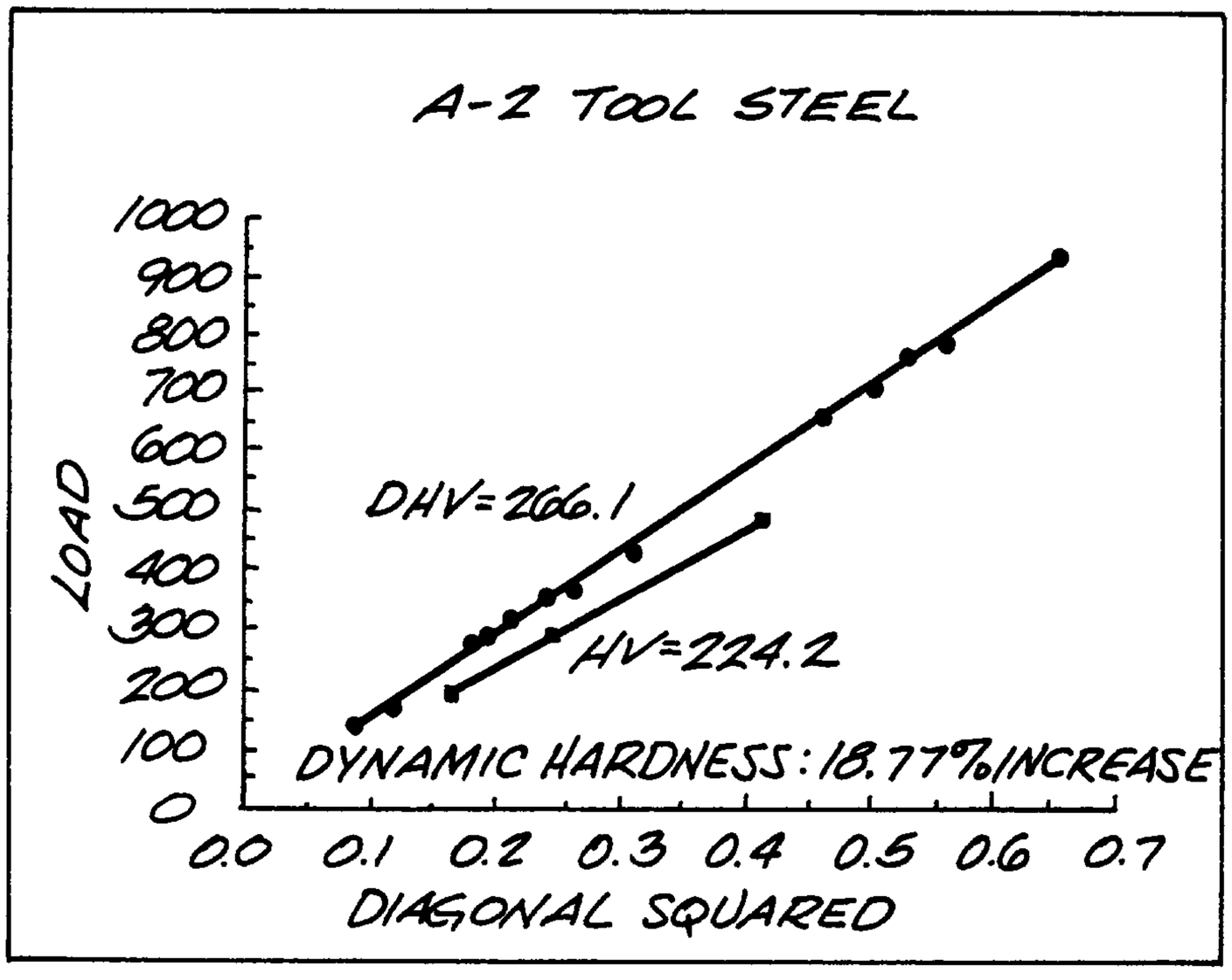

A-2 TOOL STEEL
LOAD
1000
900
800
700
600
500
400
300
200
100
0
DHV=266.1
HV=224.2
DYNAMIC HARDNESS: 18.77% INCREASE
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
DIAGONAL SQUARED

Fig. 3b

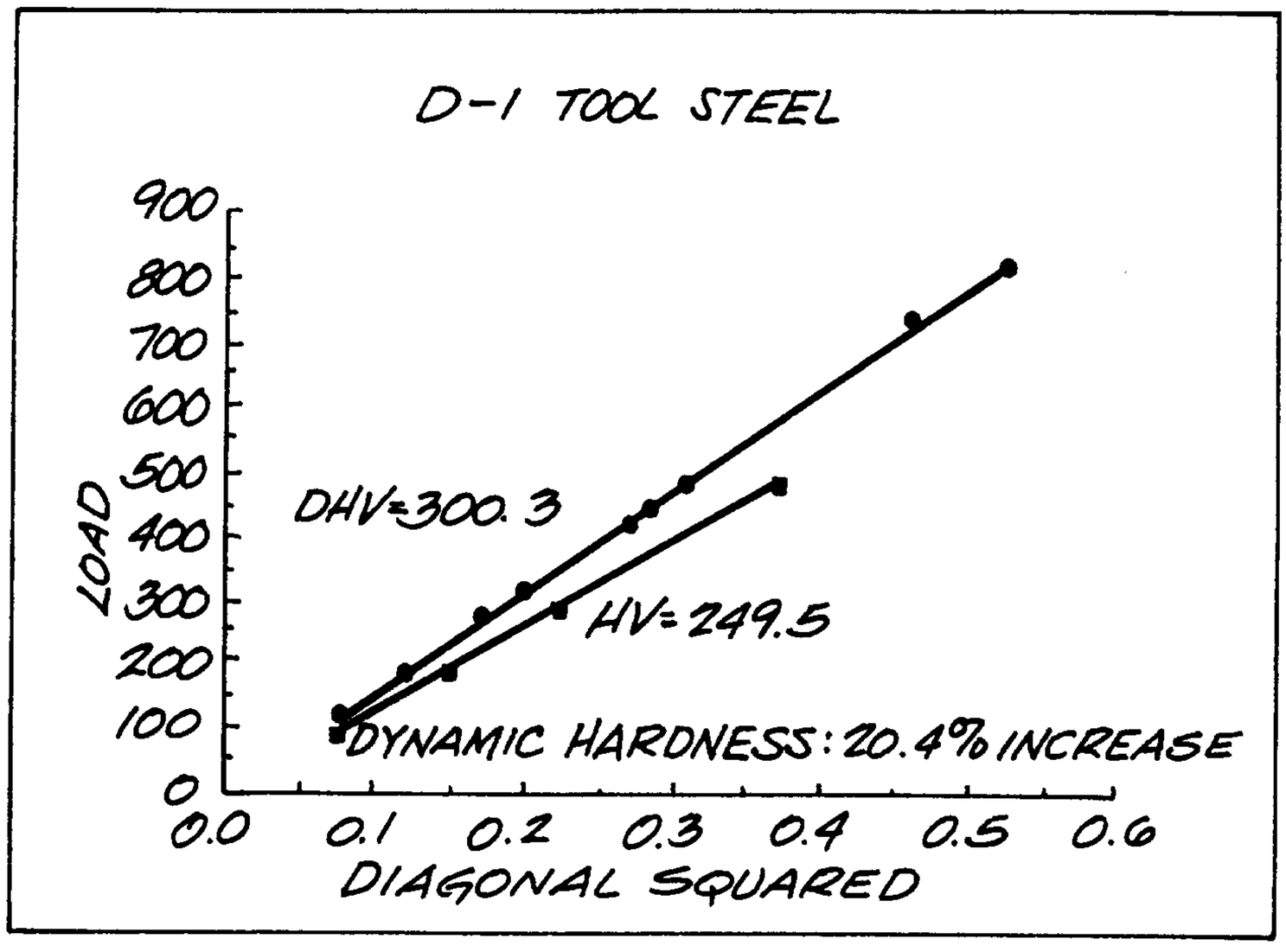

D-1 TOOL STEEL
900
800
700
600
500
400
300
200
100
0
LOAD
DHV=300.3
HV=249.5
DYNAMIC HARDNESS: 20.4% INCREASE
0.0
0.1
0.2
0.3
0.4
0.5
0.6
DIAGONAL SQUARED

Fig. 3c

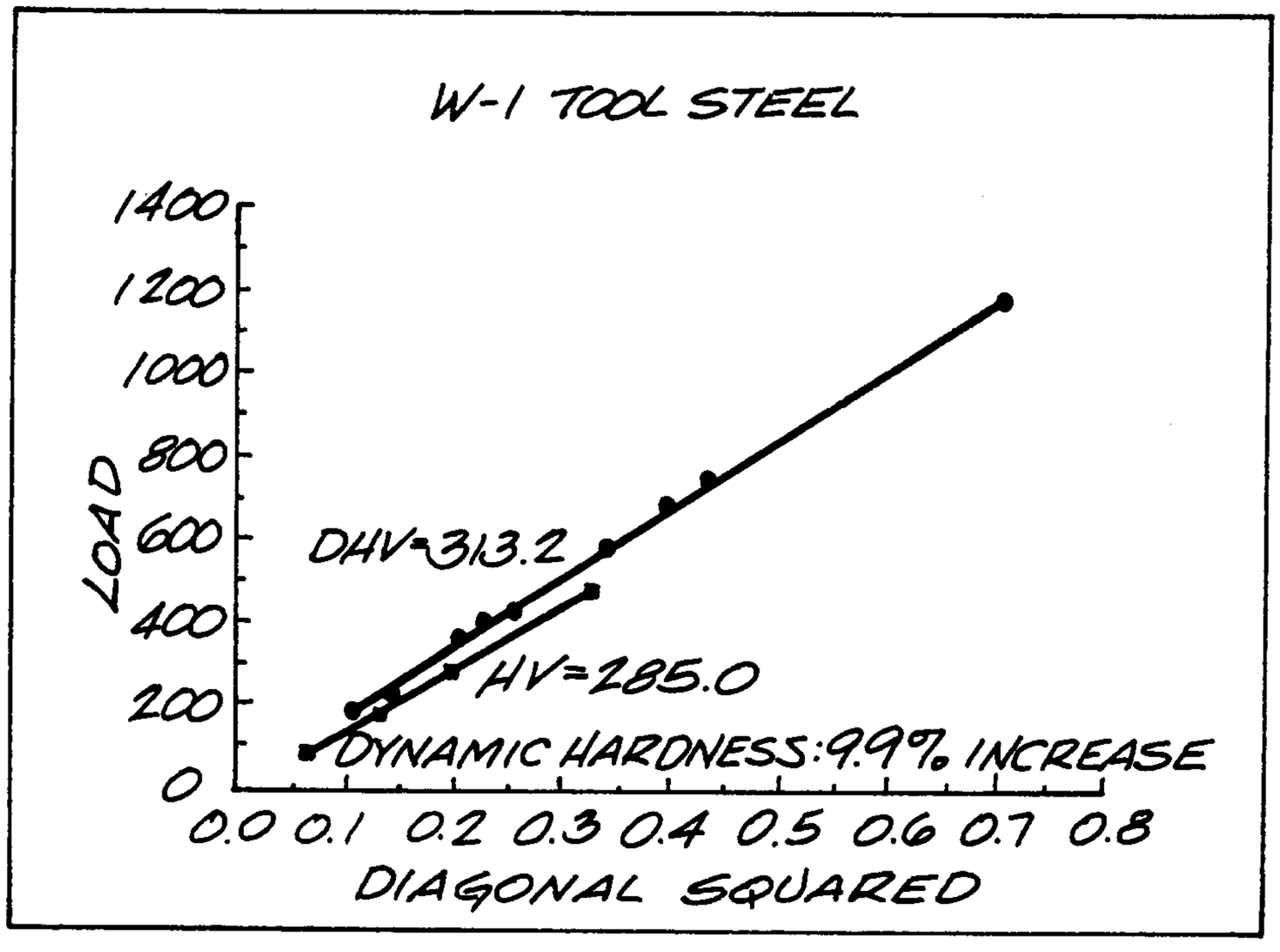

W-1 TOOL STEEL
1400
1200
1000
800
600
400
200
0
LOAD
DHV=313.2
HV=285.0
DYNAMIC HARDNESS: 9.9% INCREASE
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
DIAGONAL SQUARED

Fig. 3d

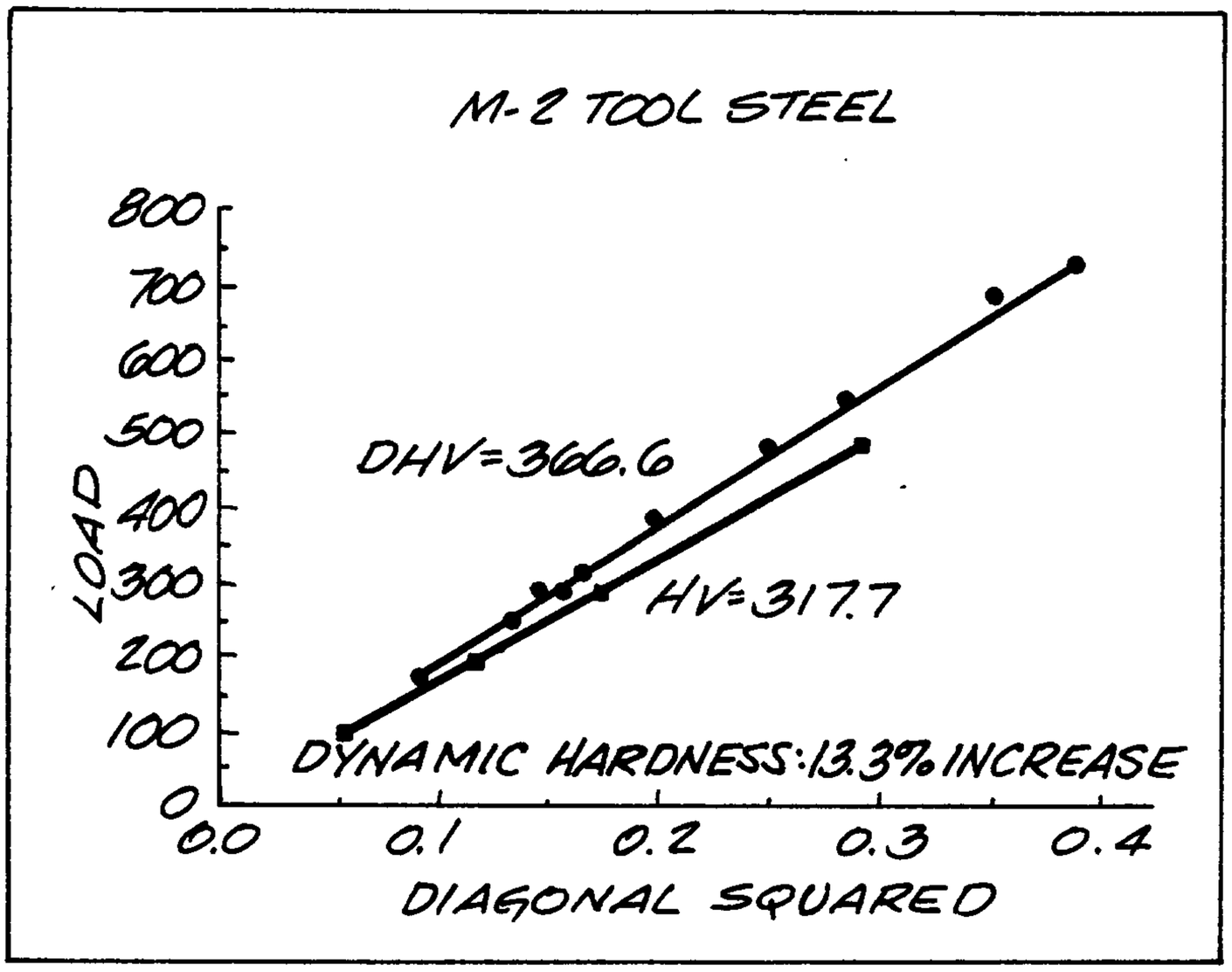

M-2 TOOL STEEL
800
700
600
500
400
300
200
100
0
LOAD
DHV=366.6
HV=317.7
DYNAMIC HARDNESS: 13.3% INCREASE
0.0
0.1
0.2
0.3
0.4
DIAGONAL SQUARED

Fig. 3e

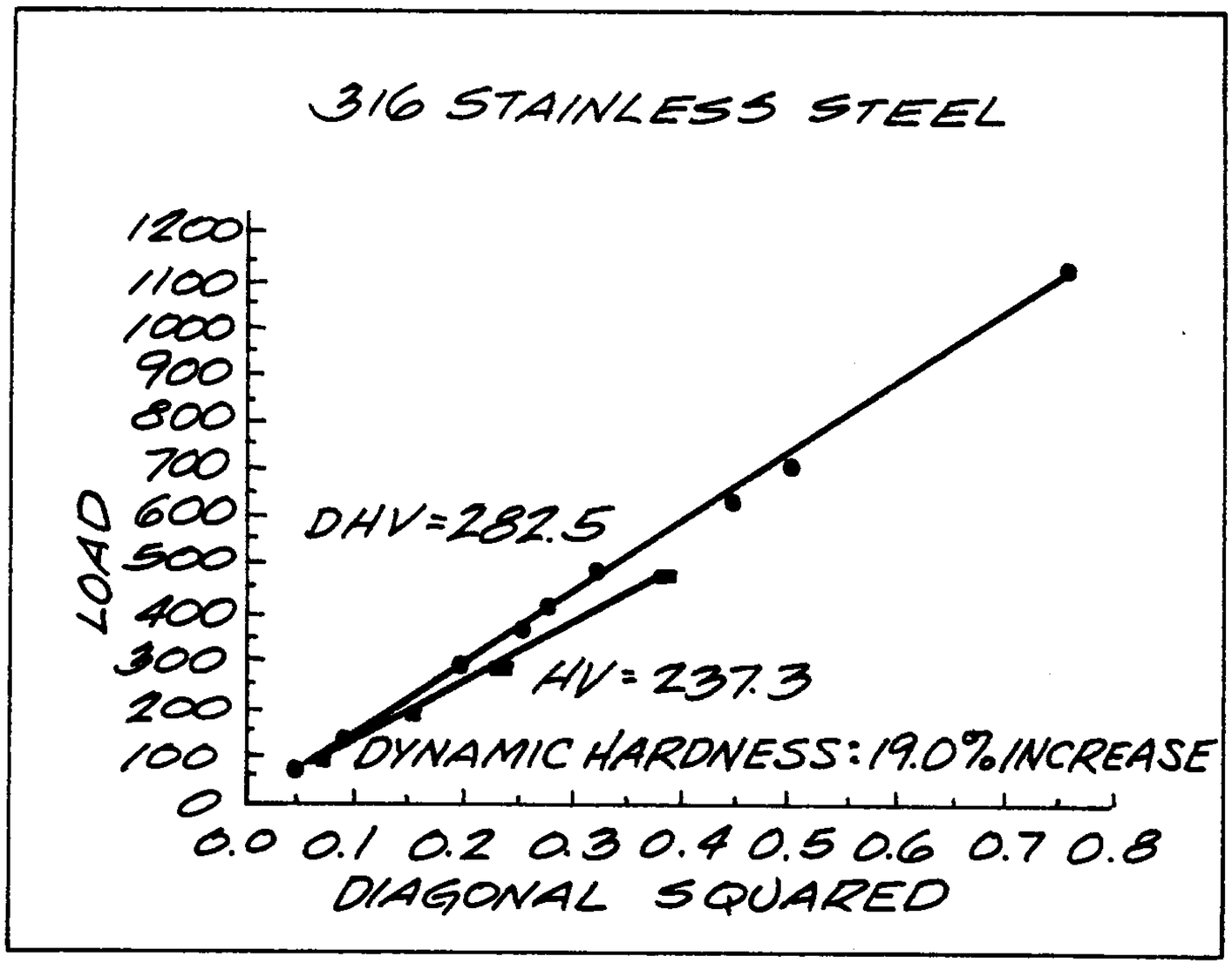

316 STAINLESS STEEL
LOAD
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
DHV=282.5
HV=237.3
DYNAMIC HARDNESS: 19.0% INCREASE
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
DIAGONAL SQUARED

Fig. 4a

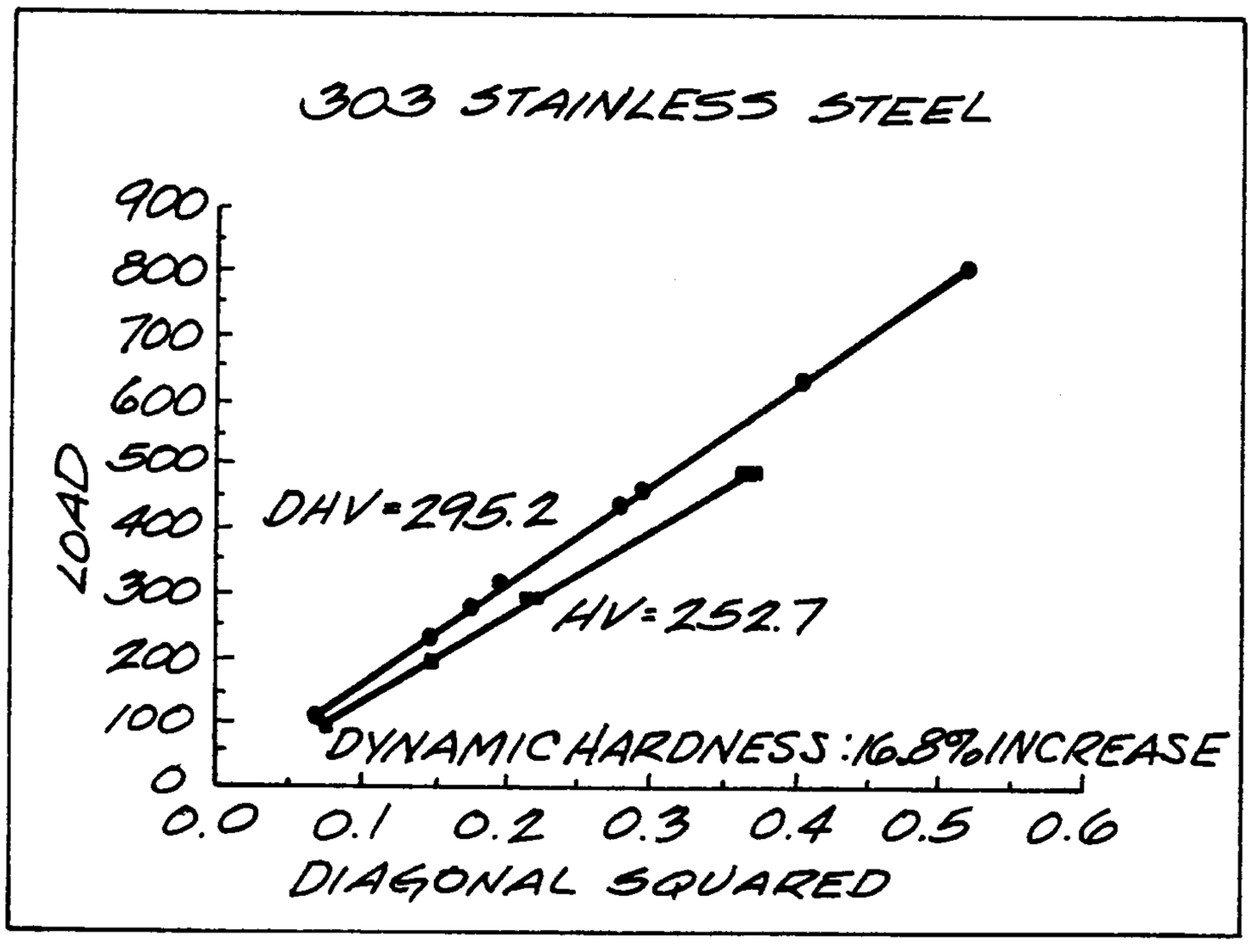

303 STAINLESS STEEL
LOAD
900
800
700
600
500
400
300
200
100
0
DHV=295.2
HV=252.7
DYNAMIC HARDNESS: 16.8% INCREASE
0.0 0.1 0.2 0.3 0.4 0.5 0.6
DIAGONAL SQUARED

Fig. 4b

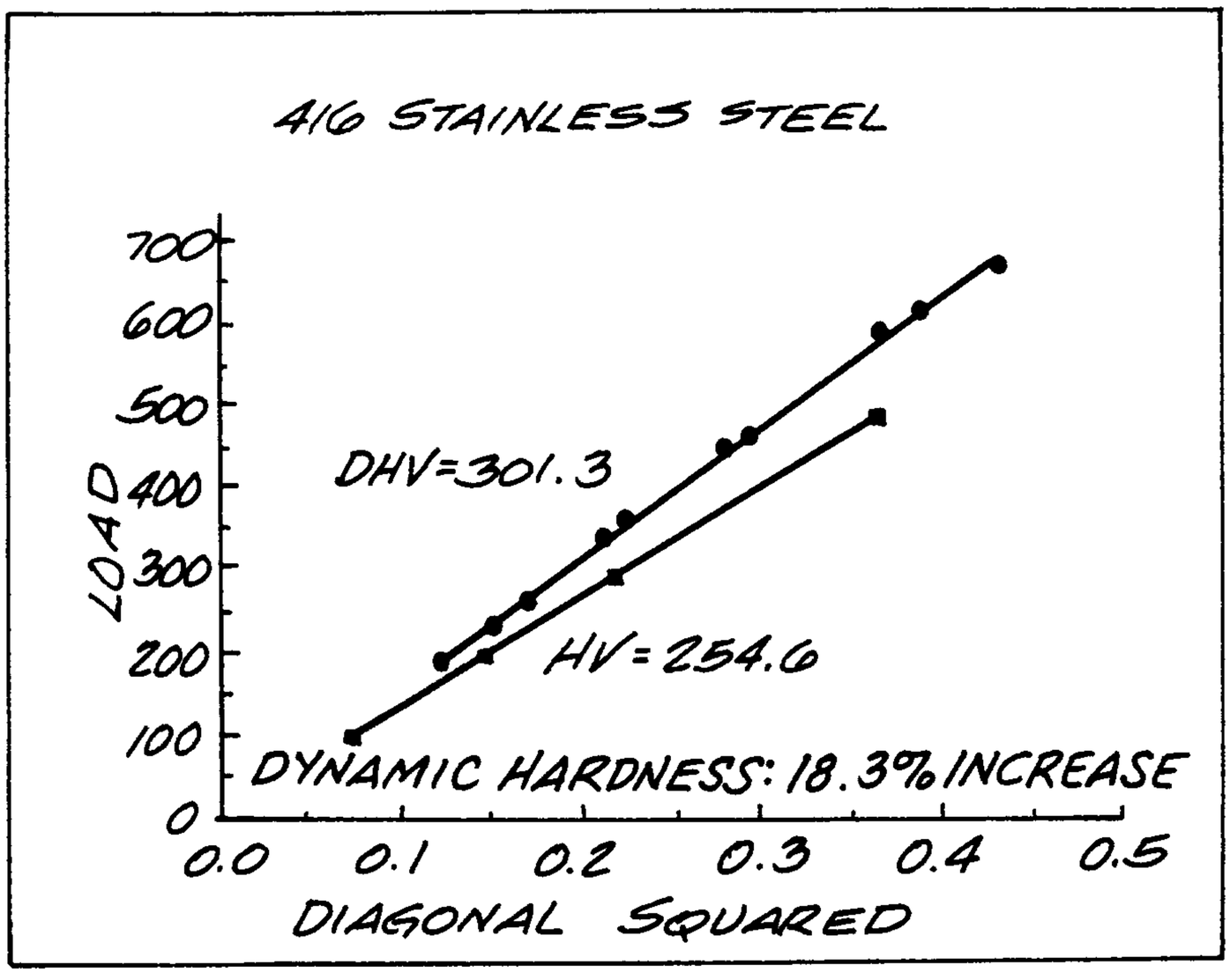

416 STAINLESS STEEL
700
600
500
400
300
200
100
0
LOAD
DHV=301.3
HV=254.6
DYNAMIC HARDNESS: 18.3% INCREASE
0.0
0.1
0.2
0.3
0.4
0.5
DIAGONAL SQUARED

Fig. 4c

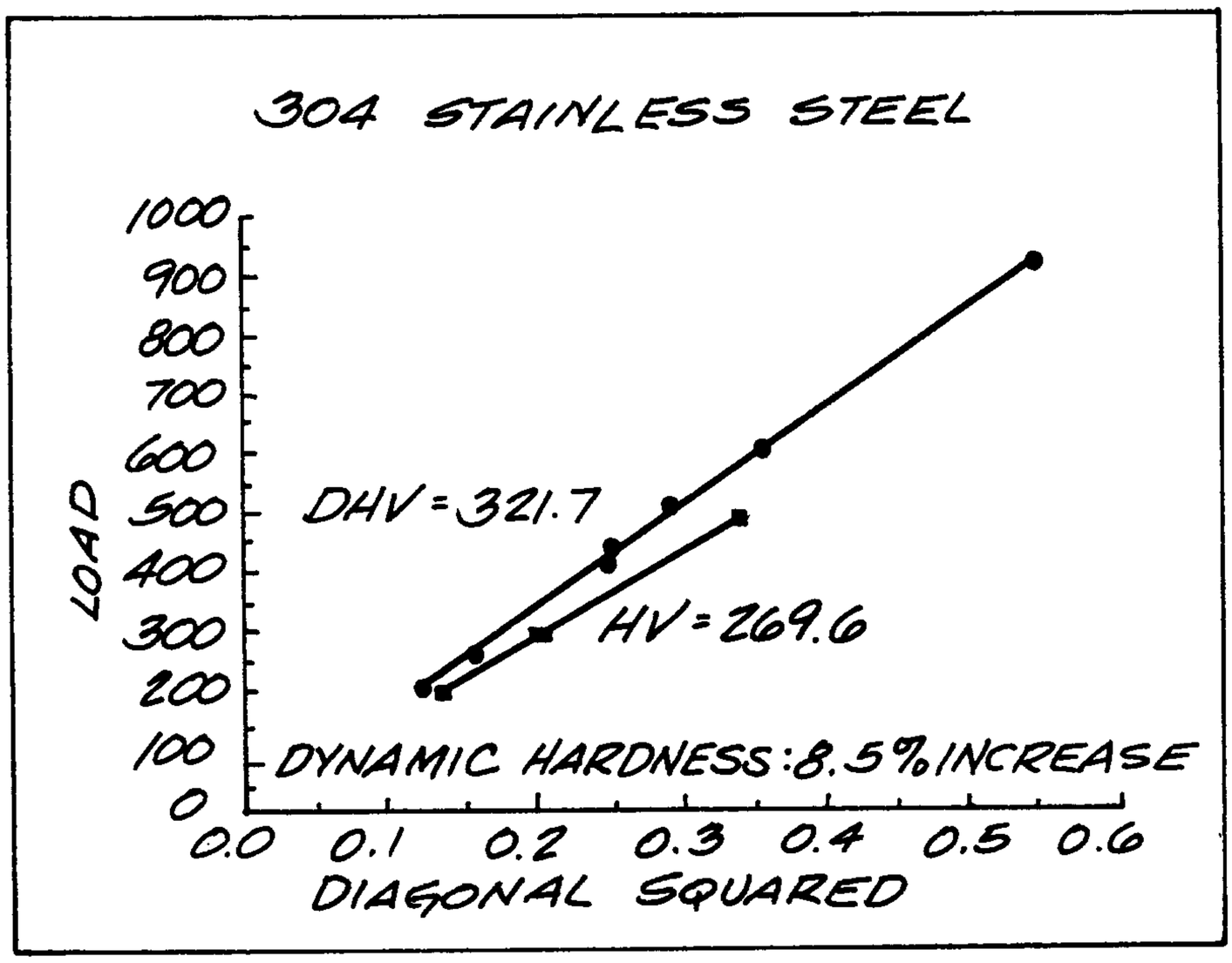

304 STAINLESS STEEL
1000
900
800
700
600
500
400
300
200
100
0
LOAD
DHV=321.7
HV=269.6
DYNAMIC HARDNESS: 8.5% INCREASE
0.0
0.1
0.2
0.3
0.4
0.5
0.6
DIAGONAL SQUARED

Fig. 4d

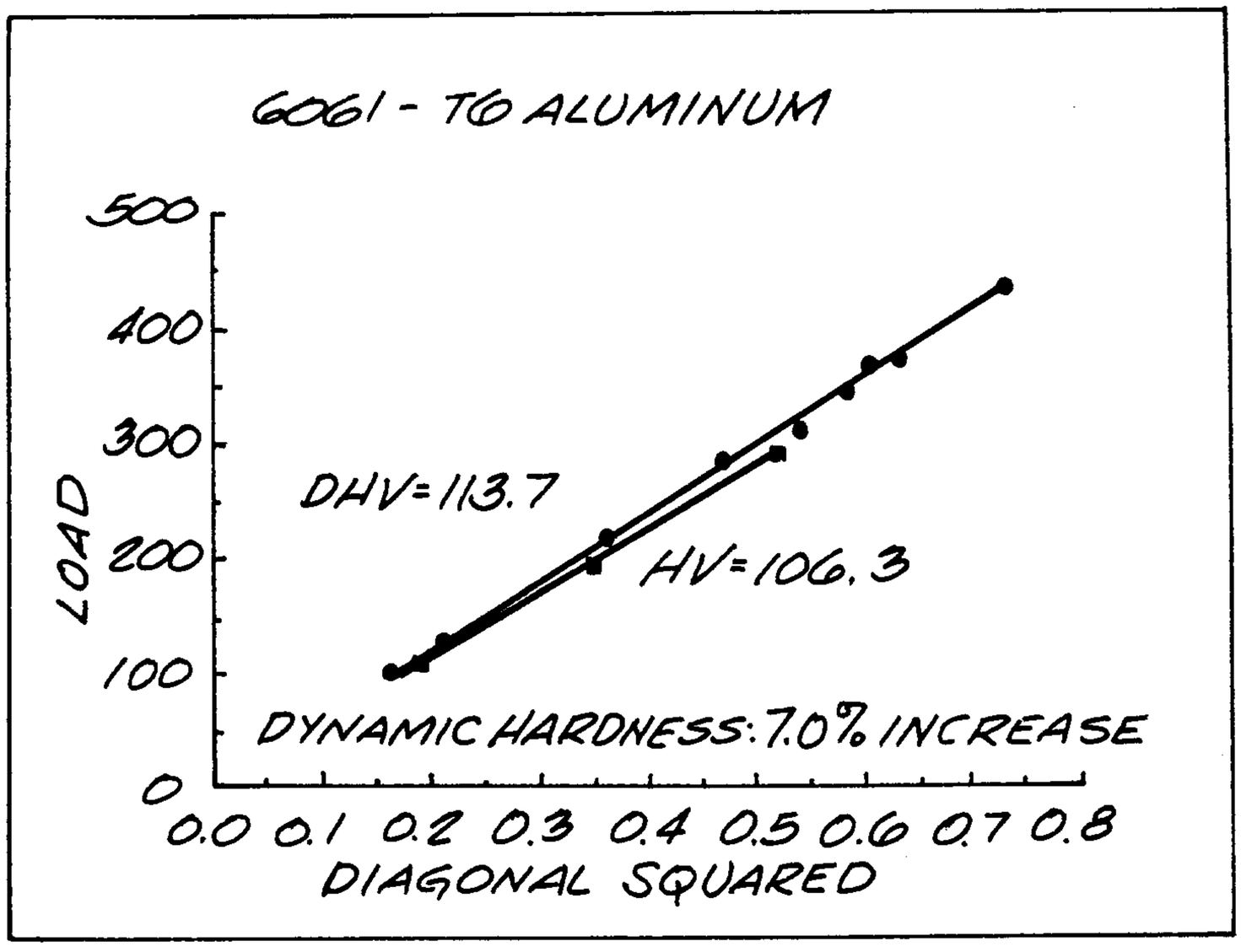

6061 - T6 ALUMINUM
500
400
300
200
100
0
LOAD
DHV=113.7
HV=106.3
DYNAMIC HARDNESS: 7.0% INCREASE
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
DIAGONAL SQUARED

Fig. 5a

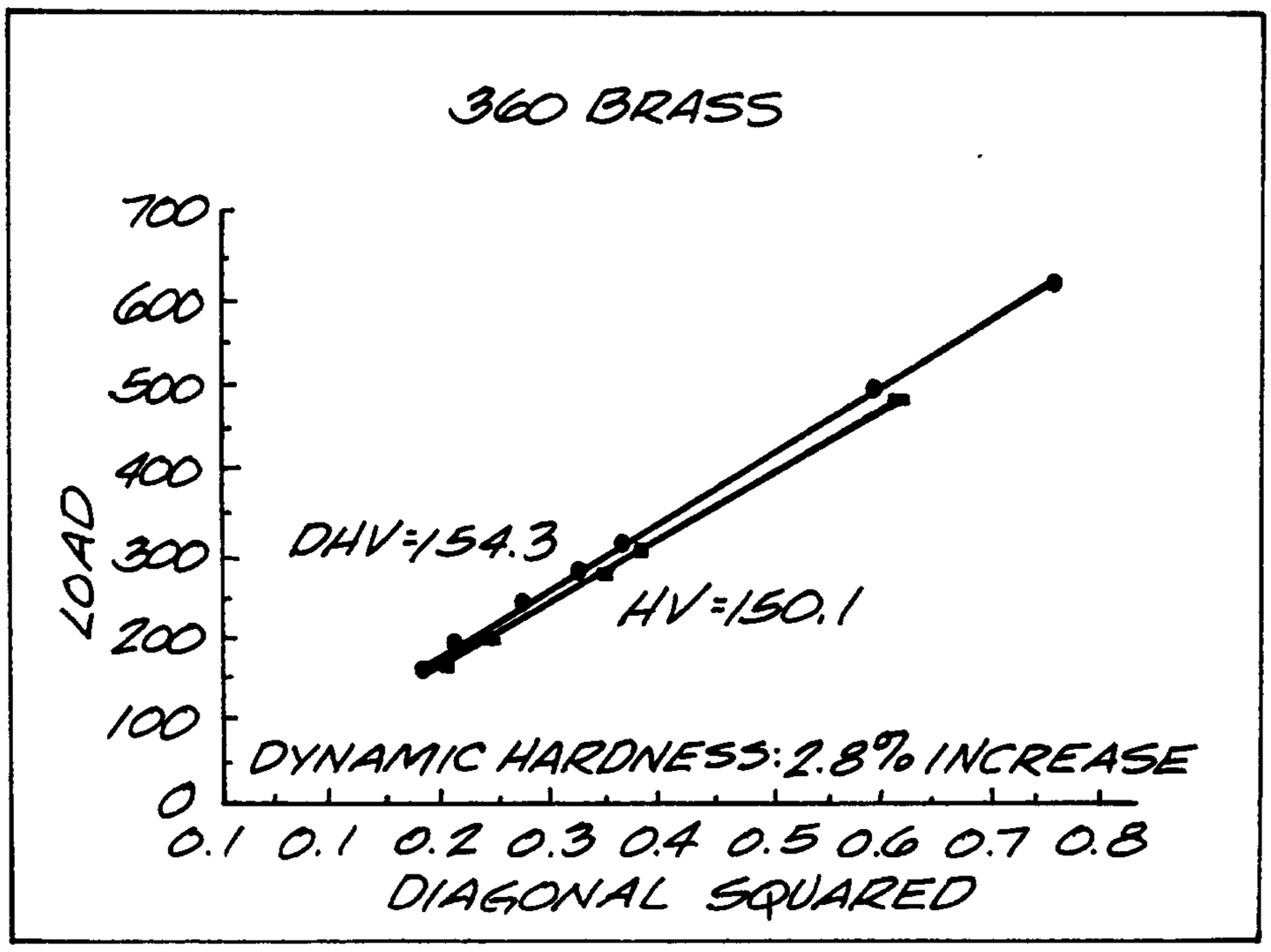

360 BRASS
700
600
500
400
300
200
100
0
LOAD
DHV=154.3
HV=150.1
DYNAMIC HARDNESS: 2.8% INCREASE
0.1 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
DIAGONAL SQUARED

Fig. 5b

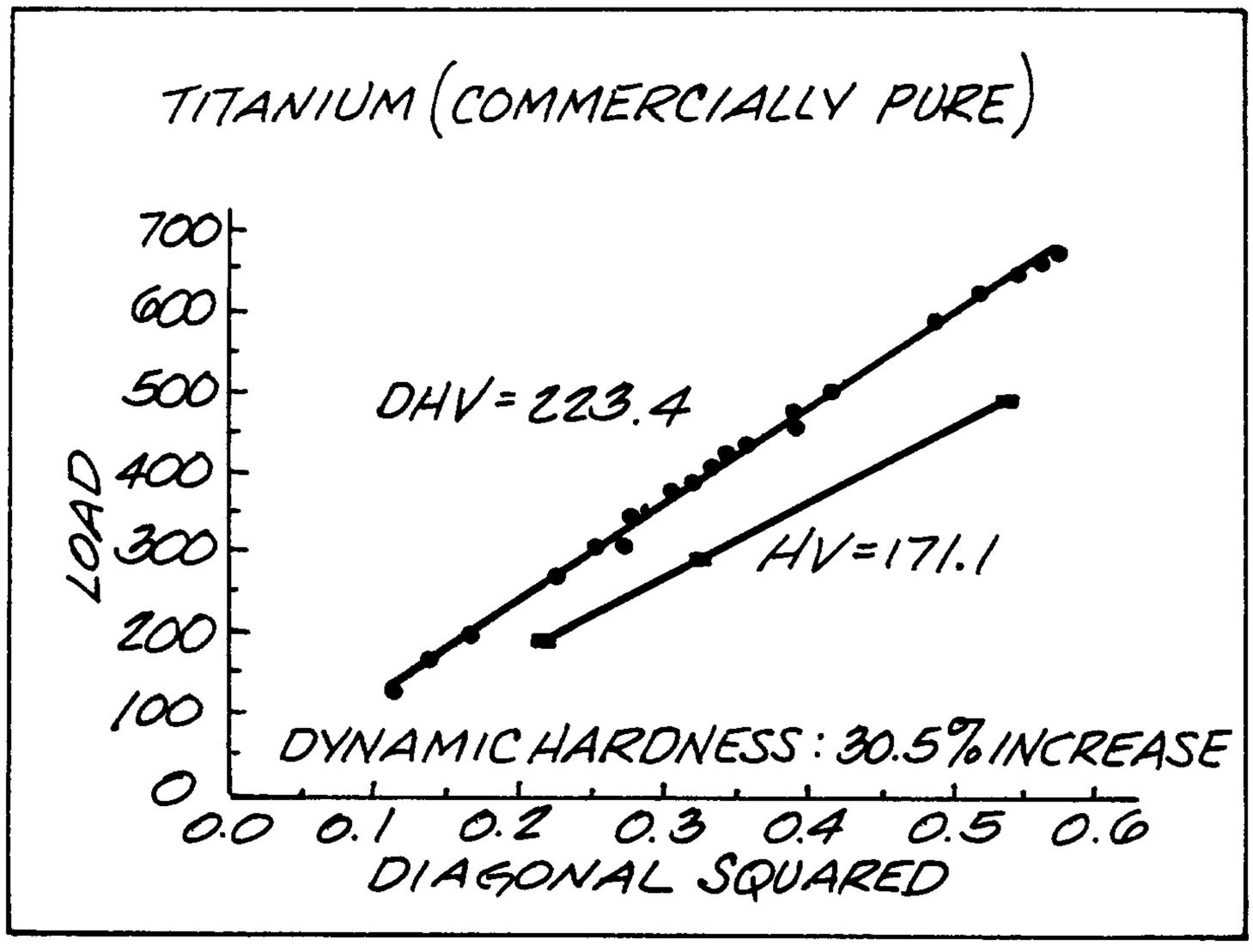

TITANIUM (COMMERCIALLY PURE)
700
600
500
400
300
200
100
0
LOAD
DHV = 223.4
HV = 171.1
DYNAMIC HARDNESS : 30.5% INCREASE
0.0
0.1
0.2
0.3
0.4
0.5
0.6
DIAGONAL SQUARED

Fig. 6a

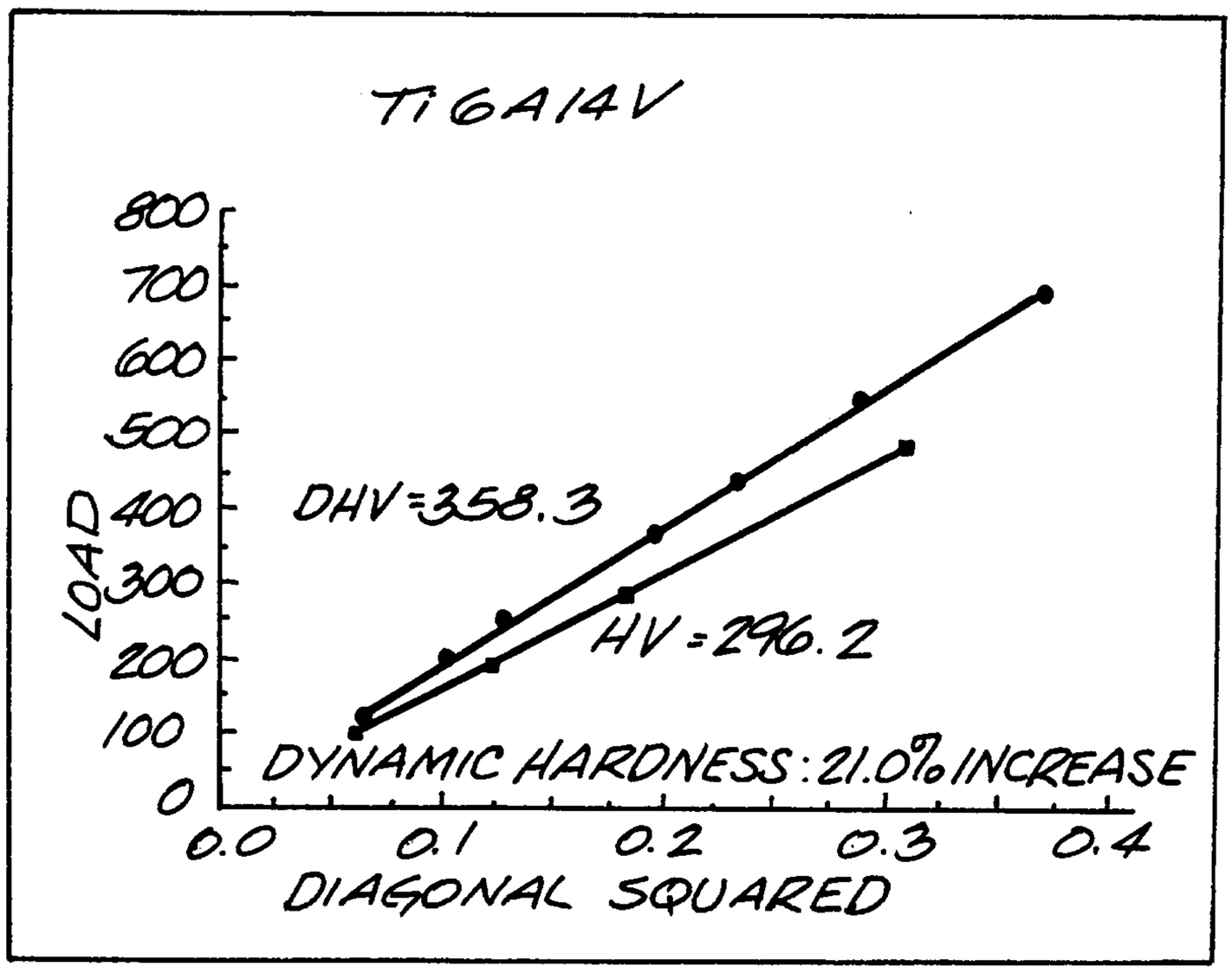

Ti 6A14V
800
700
600
500
400
300
200
100
0
LOAD
DHV = 358.3
HV = 296.2
DYNAMIC HARDNESS : 21.0% INCREASE
0.0
0.1
0.2
0.3
0.4
DIAGONAL SQUARED

Fig. 6b

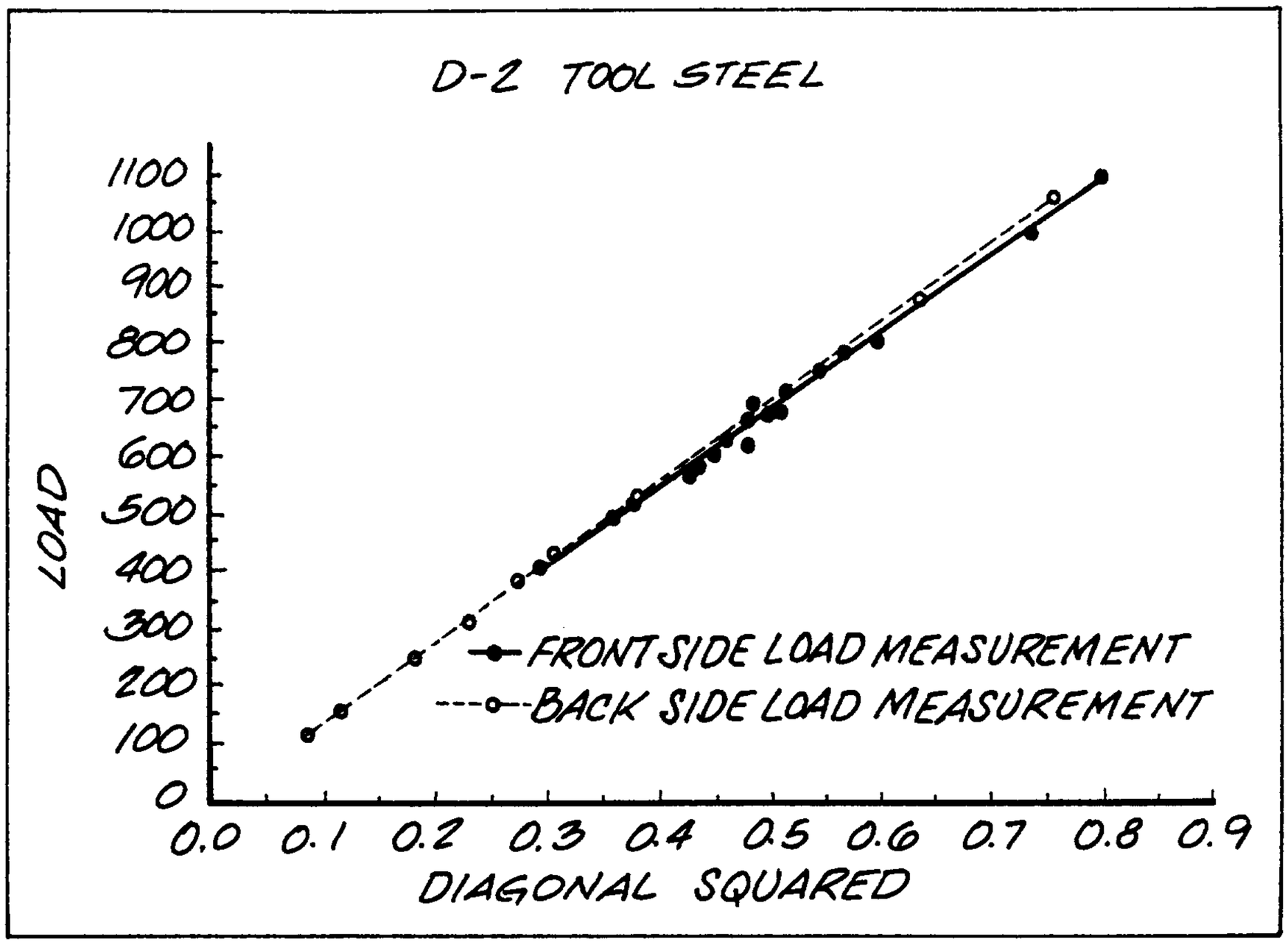

D-2 TOOL STEEL
LOAD
1100
1000
900
800
700
600
500
400
300
200
100
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
DIAGONAL SQUARED
FRONT SIDE LOAD MEASUREMENT
BACK SIDE LOAD MEASUREMENT

Fig. 7

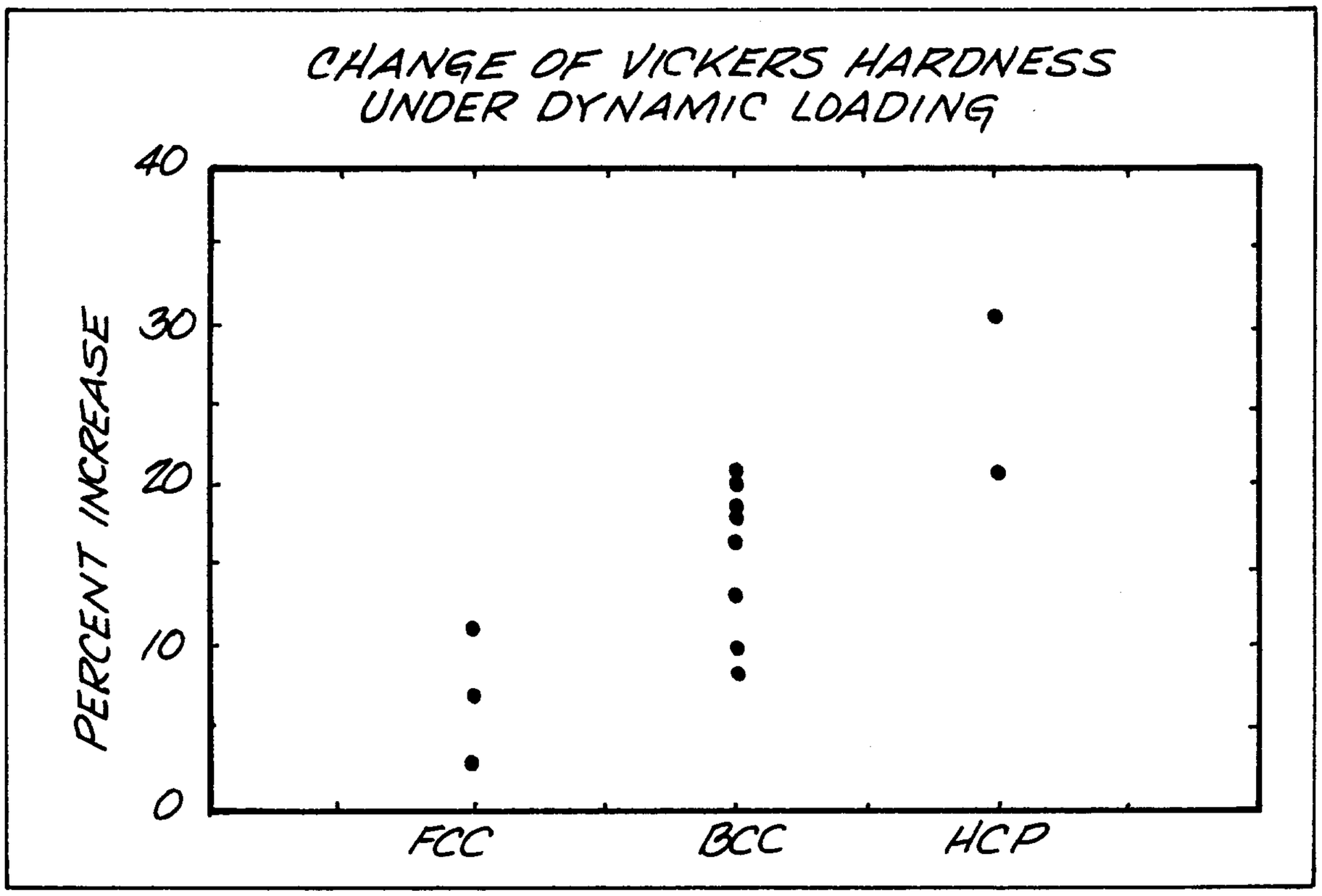

CHANGE OF VICKERS HARDNESS
UNDER DYNAMIC LOADING
PERCENT INCREASE
40
30
20
10
0
FCC
BCC
HCP

Fig. 8

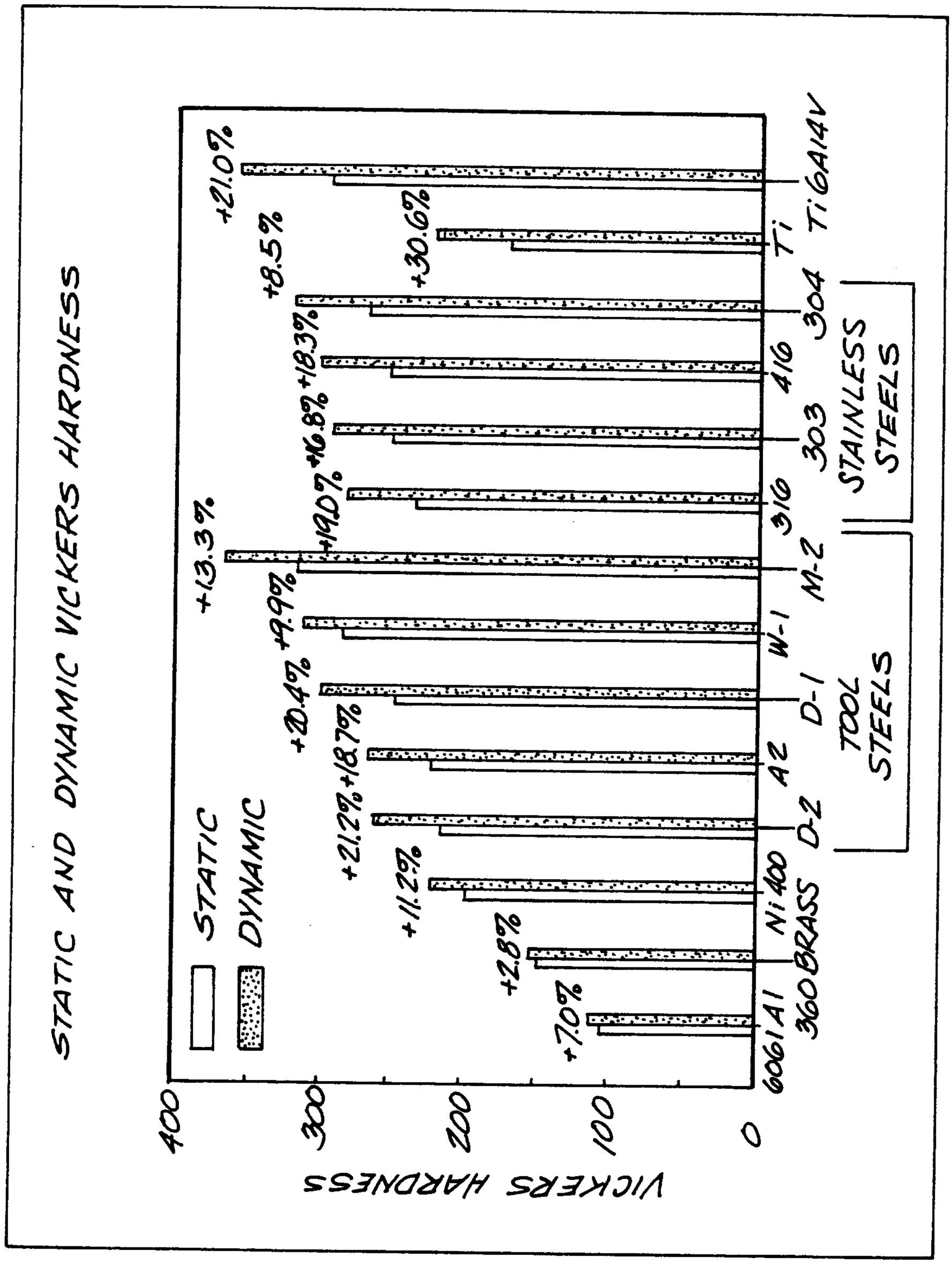
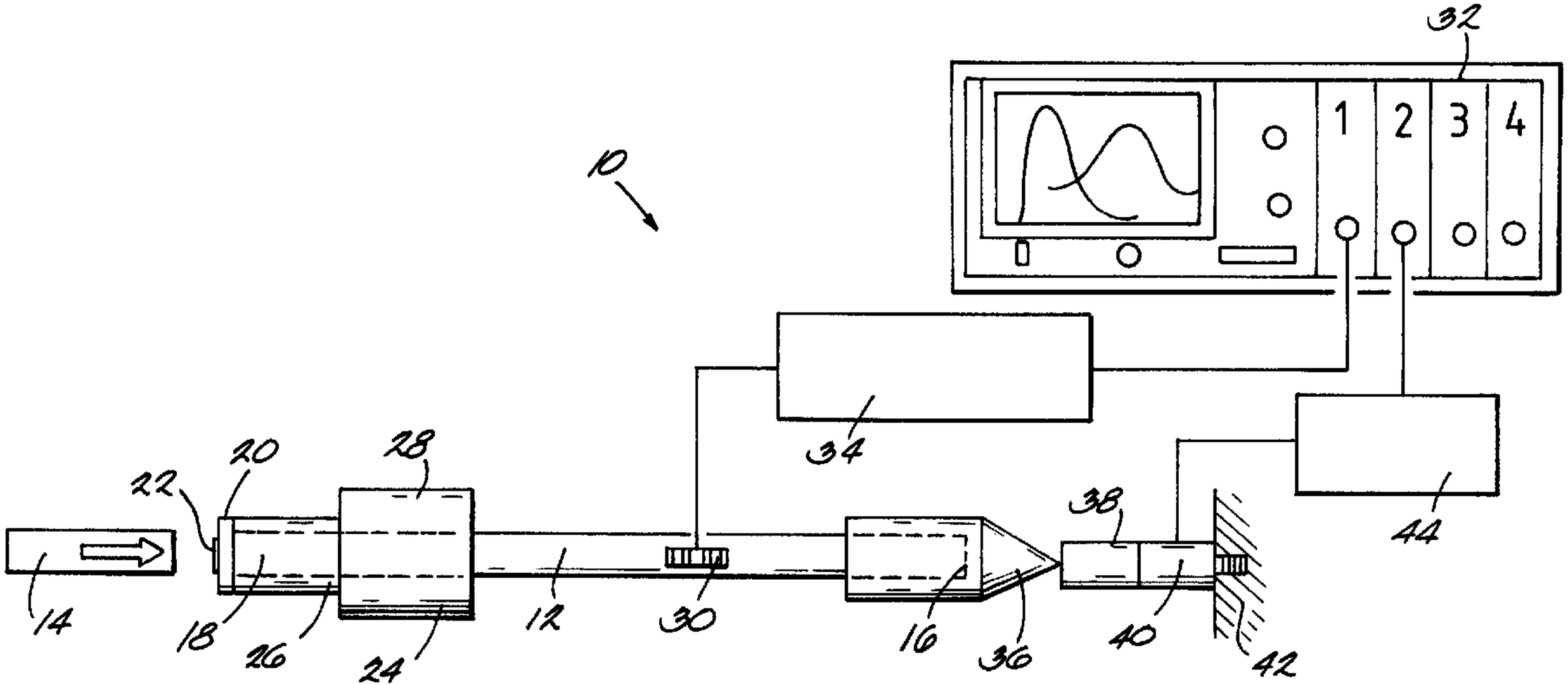

STATIC AND DYNAMIC VICKERS HARDNESS
STATIC
DYNAMIC
+13.3%
+19.0%
+10.4%
+9.9%
+21.2%
+18.7%
+11.2%
+2.8%
+7.0%
+8.5%
+30.6%
+16.8%
+18.3%
+21.0%
6061 Al
360 BRASS
Ni 400
D-2
A2
D-1
W-1
M-2
303
316
416
304
Ti
Ti 6Al 4V
TOOL STEELS
STAINLESS STEELS
400
300
200
100
0
VICKERS HARDNESS

Fig. 2


10
32
1
2
3
4
34
44
14
22
20
18
26
28
24
12
30
16
36
38
40
42