Deformation of metal brackets: a comparative study

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The orthodontic bracket is the intermediary in tooth movement. It receives force from an activated element—usually a wire—and transmits that force to the tooth. If the bracket fractures or permanently deforms, the force is not transmitted and treatment is prolonged. It would be useful, therefore, to know which bracket characteristics are associated with resistance to fracture and deformation.

Numerous types of metal brackets are available with a variety of sizes, wing designs and slot angles. Varied information about new metal bracket technology and manufacturing processes can make it difficult to choose the right bracket for meeting orthodontic goals.

Since orthodontic patients are sensitive to their appearance during orthodontic treatment, there is a demand for less conspicuous brackets. Subsequently, orthodontic manufacturers have introduced smaller metal and ceramic brackets. However, ceramic brackets may fracture with typical occlusal and orthodontic forces, while these forces would only deform metal brackets.

In order to evaluate brackets, the physical and mechanical properties of their materials must be understood. Considerable research has been done to evaluate the properties of chromium-cobalt, titanium-molybdenum, and nickel-titanium alloy wires.[1-5] However, little research has been done to evaluate how the properties of bracket materials influence the properties of brackets used in orthodontics. No attempt has been made to describe where the strengths or weaknesses lie within the configuration of a metal bracket.

Abstract

The purpose of this study was to determine the effect of material and design on the force and stress required to permanently deform metal brackets.

Fourteen types of metal brackets were categorized according to raw material composition, slot torque degree, and wing type. Five types of raw materials, three types of slot torque degree, and four types of wing design were tested using an archwire torque test developed by Flores.

An analysis of variance (ANOVA) and t-test showed that all three categories had a significant effect on the force and stress needed to permanently deform metal brackets. Of the three, raw material had the greatest effect on the amount of force.

Results showed that 17-4PH and 303S had higher yield strengths and regular twin brackets had higher resistance to deformation. Also, as slot torque degree increased, brackets deformed with less force. Result confirmed that brackets requiring the greatest stress to permanently deform were made of steel with the greatest hardness.

Key Words

Bonding • Bracket • Deformation • Stainless steel • Tensile strength

Submitted: April 1991 **Revised and accepted for publication:** March 1994 Angle Orthod 1994;64(4):283-290

Table 1
Chemical composition by percent

Raw Material	CR	Ni	MN	C	P	S	Si	Mo	Se
1. 310SS	24.0	19.0 26.0	2.0 22.0	.08	.04	.03	1.5	.75	
2. 313SE	17.0	8.0 19.0	2.0 10.0	.15	.20	.06 .17	1.0		.15 .35
3. 316L	16.0 18.0	10.0 14.0	2.0	.03	.04	.03	1.0	2.0 3.0	
4. 303S	17.0 19.0	8.0 10.0	2.0	.15	.04	.18 .40			
5. 17-4PH	15.5 17.5	3.0 5.0	1.0	.07	.04	.03	1.0		

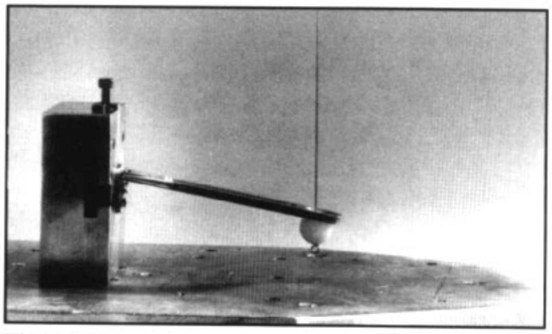
Figure 1

Figure 1
Side view of the testing fixture with a steel vice gripping the steel base disc and the torquing key engaged to an archwire.

Flores[6] compared the fracture strength of ceramic brackets and the force to permanently deform metal brackets and found that ceramic brackets were able to withstand a higher force than metal brackets. He suggested that the low forces required for metal brackets to fail indicated the brackets could become distorted during treatment when high torquing forces were applied. However, only one type of metal bracket was compared to four types of ceramic brackets.

Metal orthodontic brackets are now made from five different American Iron and Steel Institute types of stainless steel.[7,8] Nominal compositions of the five different types of stainless steel are listed in Table 1.

Austenitic stainless steel has been used the most in orthodontics. This alloy contains about 18% chromium and 8% nickel, and is commonly known as 18-8 stainless steel. The nickel content has a stabilizing effect on austenite so that the face-centered cubic structure is stable even at room temperature. Stainless steel type 303 was the first chrome-nickel, free-machining stainless steel ever made.

Stainless steel type 303SE is a free-machining 18-8 chrome-nickel steel to which selenium has been added. Selenium makes it more machinable, but it also detracts from hardness and strength.

Stainless steel types 316L and 310SS are molybdenum-bearing austenitic steels with increased percentages of nickel. These steels have higher tensile and creep strengths at elevated temperatures.

Stainless steel type 17-4PH is a martensitic precipitation hardened stainless steel, which offers high strength and hardness and excellent corrosion resistance. It has good fabricating characteristics and can be age-hardened by a single, low temperature treatment.[8,9]

A definition of terms is necessary for a better understanding of the mechanical properties measured in this study.

Hardness is described as the resistance offered by the material to indentation. Hardness of a material is dependent on its strength. Even though there is no direct constant of proportionality, the higher the strength of a material, the greater its hardness. Strength properties of the tested material can be approximated using standard tables available for ultimate tensile strength and equivalent hardness.[1012]

Tensile strength is the maximum load sustained by the material prior to fracture, divided by the original cross-sectional area of the material. It is of value in orthodontics as a metal quality indicator since it defines the maximum force the mate-

Table 2

1) Mini Taurus, Rocky Mountain Orthodontics, Denver, Colo.
2) Mini Diamond, Ormco, Glendora, Calif.
3) Single, Ormco, Glendora, Calif.
4) Single, Ormco, Glendora, Calif.
5) Mini Twin, A-Company, San Diego, Calif.
6) Regular Twin, A-Company, San Diego, Calif.
7) Single, A-Company, San Diego, Calif.
8) Regular Twin, Unitek, Monrovia, Calif.
9) Regular Twin, Unitek, Monrovia, Calif.
10) Single, Unitek, Monrovia, Calif.
11) Uni Twin,Unitek, Monrovia, Calif.
12) Master (1), American Orthodontics, Sheboygen, Wisc.
13) Advantage, T. P. Orthodontics, LaPorte, Ind.
14) Master (2), American Orthodontics, Sheboygen, Wisc.

Table 3
Description of brackets

Bracket ID Number	Number Tested	Raw Material	Slot Degree	Wing Type
1	10	316L	12	Mini Twin
2	10	17-4PH	12	Mini Twin
3	10	303SE	0	Single
4	10	303SE	12	Single
5	10	17-4PH	12	Mini Twin
6	10	310SS	12	Reg Twin
7	10	310SS	0	Single
8	10	303S	12	Reg Twin
9	10	303S	7	Reg Twin
10	10	303S	0	Single
11	10	303S	12	Mod Twin
12	10	316L	12	Mini Twin
13	10	316L	12	Mod Twin
14	10	17-4PH	12	Mini Twin

rial will withstand without breaking.[11-12]

Plastic or permanent deformation is a permanent change in shape. This change in shape is brought about by a stress in excess of the yield strength of the material.[11-12]

Yield strength of a material is the point where plastic flow starts under a continuously increasing load.

Force is a mechanical action of one body on another that tends to deform the receiving body.[13]

Force at failure for the metal brackets is considered to be the point where they permanently deform. However, this is a gradual transformational arbitrary point where there is no clear-cut yield point on the stress-strain curve.[11]

Stress is the intensity of internal force per unit of associated area.[13]

Stress at failure for the metal brackets represents the stress placed on the brackets at the point of failure.

The main objective of this study was to determine if the effects of material and design (slot torque degree and wing type) on the force and stress required to permanently deform metal brackets were significant. By evaluating the effects of material and design on the deformation of brackets, a better understanding of their interplay and importance may be reached. A secondary objective of this study was to see if there was a direct correlation between micro hardness and stress to deform metal brackets.

Methods and materials

An archwire torque test was used to determine the force needed to deform brackets; this involved ligating a full-size rectangular archwire into the slot of a bracket bonded to a steel base, mounting the base in a holding vise, and engaging a torquing key. The torquing key was activated by an Instrom stress-testing machine until the bracket was permanently deformed as described by Flores.[6] This method (Figure 1) produced consistent and repeatable data.

Fourteen types of commercially available metal edgewise brackets were tested (Table 2). A total of 140 brackets – 10 of each type – were tested for the force and stress needed to permanently deform them. All brackets were maxillary central brackets, with an .018 x .025 inch slot size.

Three variables (material, slot torque, and wing type) were observed to compare how different materials and designs affected the force and stress required to deform metal brackets (Table 3). Five steels (310S, 316L, 303SE, 303, and 17-4PH), three slot torque degrees (0, 7, and 12), and four wing types (mini twin, single, regular twin, and modified twin) were tested.

Regular twin brackets had four wings and standard size occlusal-gingival (0.150") and mesial-distal (0.160") dimensions. Mini twin brackets had four wings, but were approximately 30% smaller in the occlusal-gingival dimension. Modified twin brackets had four wings were interconnected mesiodistally. Single brackets had two wings (Figures 2A-D).

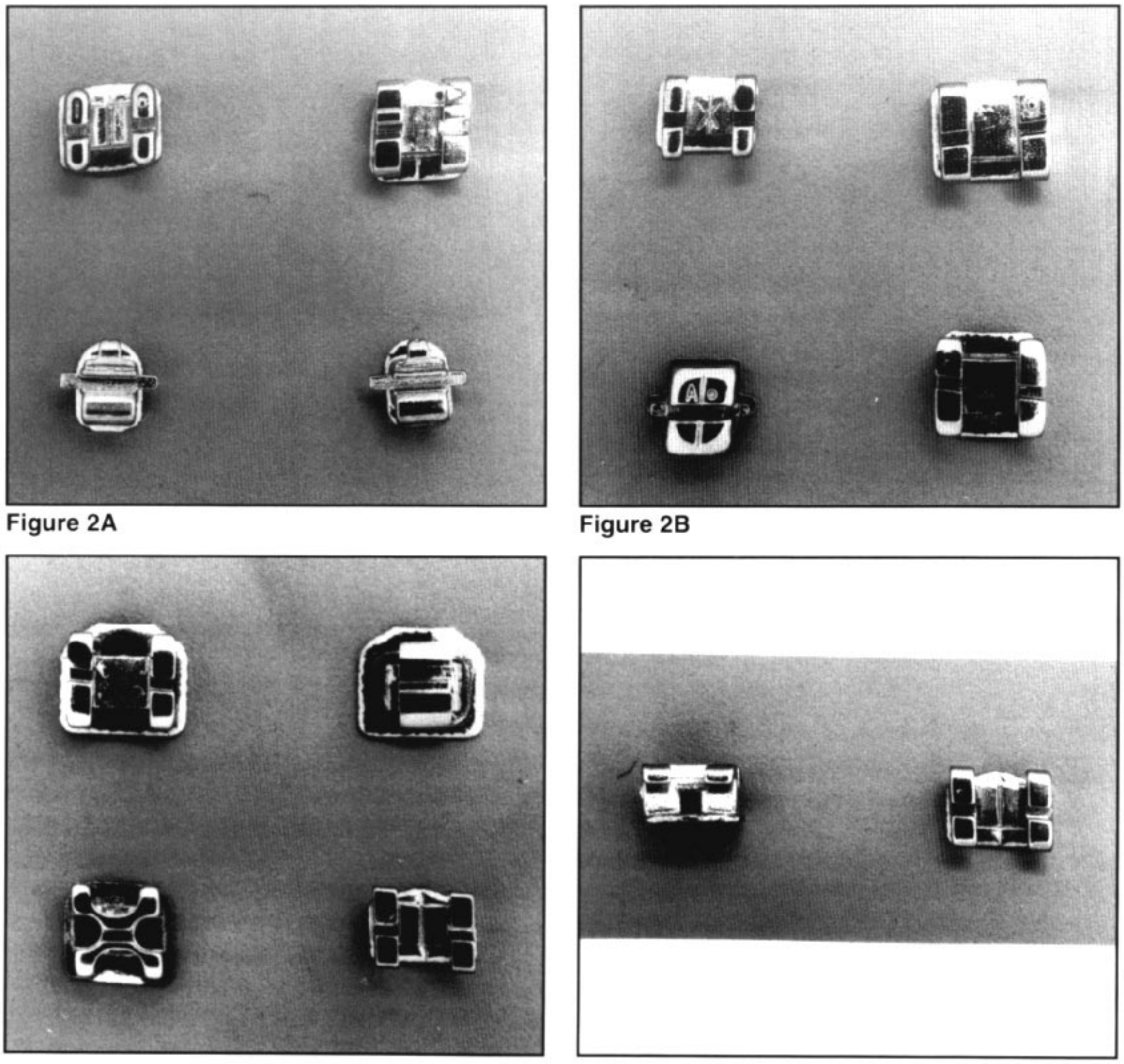

Figure 2A

Figure 2B

Figure 2C

Figure 2D

Figure 2A-D
Anterior views of the brackets tested. Clockwise from the top left of each photo, the bracket identification numbers are:
A: 1, 2, 4, 3
B: 5, 6, 8, 7
C: 9, 10, 12/14, 11 (Brackets 12 and 14 are identical in design but are composed of different material.)
D: 13 (top and anterior views).

Four types of brackets (#s 3, 4, 8, and 9) were divided into two groups compared in the slot torque category (Table 3). Each group had two types of brackets with the same material and wing type but with different slot torque degrees.

Full size (.0188 x .025) stainless steel archwire of high tensile strength (340 ksi) was used to transmit the force directly to the brackets.[7] The archwire was ligated to the brackets with elastic ligatures (Figure 3).[6]

A custom-made torquing key, three inches in length with two slots .240 inches apart, was engaged to the archwire (Figure 1). An Instrom machine was used to pull the torquing key at a crosshead speed of 10 mm/min until the bracket was permanently deformed as described by Flores.[6] As the metal bracket deformed, the slope indicating applied torsional force slowly decreased. The force required to permanently deform the metal bracket was determined to be the point where the line's slope began to decrease.

The beam bending formula developed for Flores was used to convert force to stress at failure. It was based on the bracket's dimensions and numerically calculated by the finite element method. Force to deform is force in pounds exerted by the Instrom machine at the point of permanent bracket deformation from which stress to deform values, in ksi, were calculated.[6]

The load values (P, in lbs) applied to the different bracket types were converted to stress (S_F, measured in psi), using the following Beam Bending (Flexure) Formula 13 (Figure 6):

$$S_f = \frac{M \cdot C}{I} \quad \text{(eqn 1)}$$

where:

S_F=the maximum stress in the beam
M=the bending moment at the section of interest
C=the distance from the centroidal axis of the beam
I=the moment of inertia

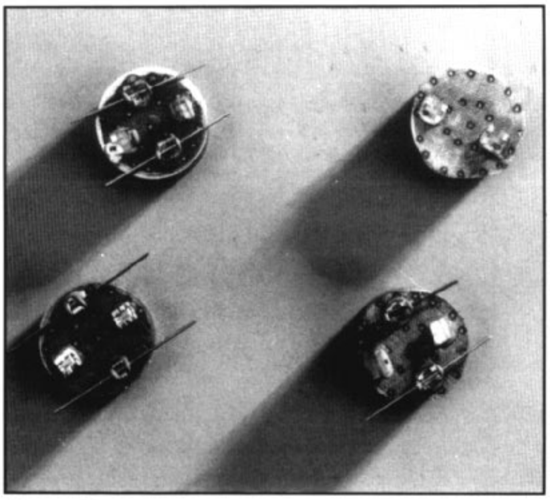

Figure 3

The following values from the testing model were applied to the Bending Formula, after each bracket type was measured, in the following manner (Figure 4).

$$M = \frac{3 \cdot P}{d/2} \cdot D \quad \text{(eqn 2)}$$

C=c/2

$I = 1/12 \cdot a \cdot c3$

therefore,
$$SF = \frac{\frac{3 \cdot P}{d/2} \cdot D \cdot c/2}{1/2 \cdot a \cdot c^3} \quad \text{(eqn 3)}$$

where:

- a=the width of the bracket's wing(s)
- c=the depth of bracket's wing at base of the slot
- d=the distance of the applied force on the bracket
- 3=the length of the torquing key in inches
- D=the distance from applied force to point of failure
- P=load

Statistics

Statistical analysis comparing each group was performed using one-way ANOVA. Standard deviation, standard error, variance, and coefficient of variance were calculated differences tested at the 0.05 level and reported as significant. The analysis was used to check for significance between (1) loads and brackets, (2) stress and brackets, (3) raw material (stainless steel type) and load, (4) raw material (stainless steel type) and stress, (5) wing type and load, and (6) wing type and stress.

The null hypothesis for this analysis was: "there is no significant difference between the failure strengths of the bracket types tested."

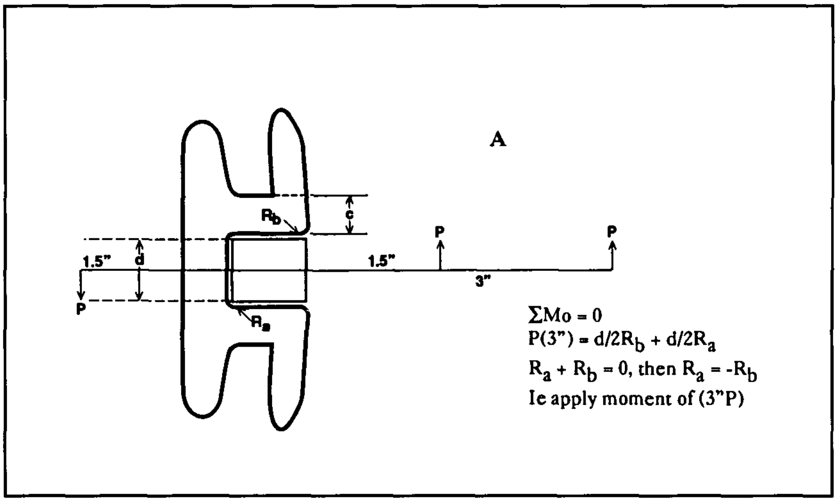

Figure 4A

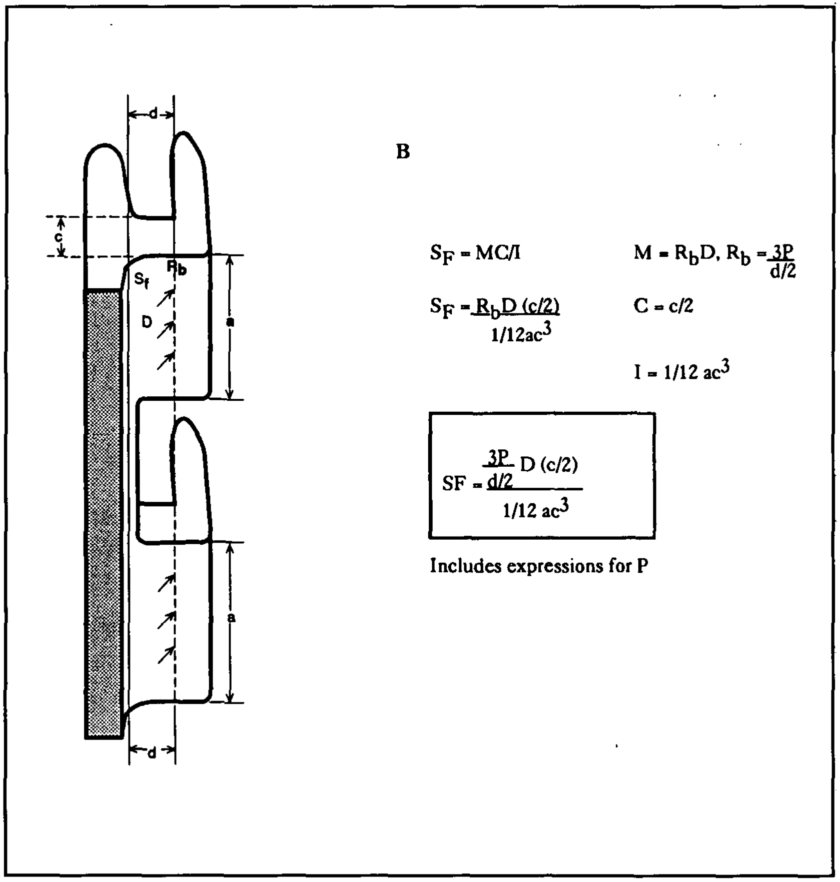

Figure 4B

Figure 3
Top view of steel base discs with brackets bonded and archwires ligated.

Figure 4A-B
Derivation of S(F) from the Beam Bending Formula, as applied to the bracket testing design.
A. Lateral view of a bracket with an archwire in the slot.
B. Cross-section at the base of the bracket showing the dimensions measured for each type of bracket.

Table 4
Force and stress at failure for each type of bracket

Bracket ID No.	Number Tested	Force Mean	Force SD	Stress Mean	Stress SD
1	10	.145	.019	163.6	21.5
2	10	.127	.015	83.7	9.4
3	10	.134	.024	104.9	18.8
4	10	.102	.017	79.5	13.6
5	10	.227	.013	370.9	21.5
6	10	.163	.019	62.1	7.0
7	10	.117	.014	65.4	7.7
8	10	.210	.017	108.5	8.5
9	10	.236	.019	122.0	9.7
10	10	.270	.020	171.1	12.7
11	10	.215	.014	440.1	27.8
12	10	.122	.014	103.5	12.1
13	10	.119	.013	134.6	14.8
14	10	.247	.012	207.7	10.8

Force in failure in lbs
Stress at failure in ksi

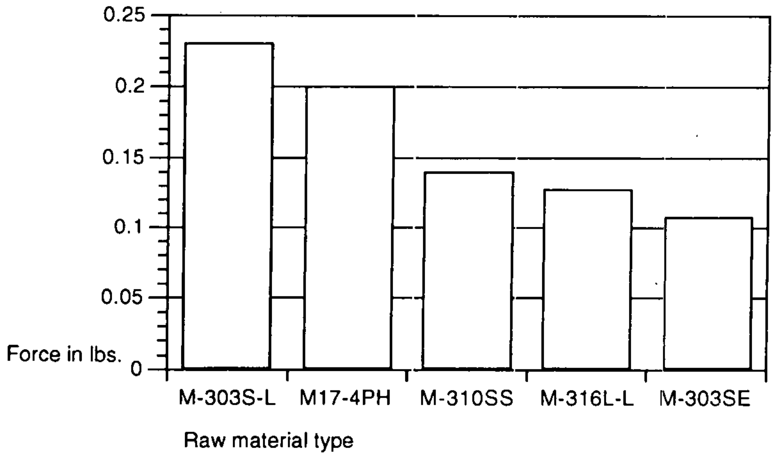

Figure 5

Figure 5
Effect of raw material on force

Table 5
Effect of material type ranked by force

Material Type	Number Tested	Force Mean	Force SD
1. 303S	40	.233	.029
2. 17-4PH	30	.200	.055
3. 310SS	20	.140	.029
4. 316L	30	.129	.019
5. 303SE	20	.118	.026

Results

The measured forces and calculated stresses needed to permanently deform the various brackets are shown in Table 4. Average force values varied from 0.012 to 0.270 lbs. Bracket type 10, a conventional single wing bracket with no built-in torquing angle, required the highest force to deform

Material

Force values show the behavior of the material design parameters together. For the five material types, the mean forces needed to permanently deform brackets ranged from 0.233 lbs for 303S to 0.118 lbs for 303SE. Forces for 303S and 17-4PH were significantly higher than those for the rest of the brackets (Table 5 & Figure 5).

Stress values show the behavior of the material independent of design. The stress calculated from the force to deform under the material type category ranged from 221.7 ksi for material type category ranged from 221.7 ksi for

17-4PH to 63.7 ksi for 310SS. Mean stresses to deform 303S and 17-4PH were significantly higher than those for 317L, 303SE, and 310SS (Table 6 & Figure 6).

Wingtype

Forces required to deform under the wing type category ranged from a high of 0.203 lbs. for the regular twin to a low of 0.156 lbs. for the single wing bracket. The regular twin bracket was the only one with a mean significantly higher than the other three wing types (mini twin 0.174 lbs, modified twin 0.167 lbs, and single 0.156 lbs) Table 7 and Figure 7).

Slottorque

Forces needed to deform under the slot torque category were 0.102 lbs for the 12 degree torque bracket (ID 4) and 0.134 lbs. for the 0 degree torque bracket (ID 3) in one comparison. In the other comparison, forces to deform were 0.210 lbs. for the 12 degree torque bracket (ID 8) and 0.236 lbs. for the 7 degree torque bracket (ID 9).

Discussion

The distinction between force and stress must be made very clearly. Strength in engineering is re-

Table 6
Effect of material type ranked by stress

Material Type	Number Tested	Stress Mean	Stress SD
1. 17-4PH	30	221.7	120.4
2. 303S	40	210.5	137.3
3. 316L	30	133.9	29.6
4. 303SE	20	92.2	20.7
5. 310SS	20	63.7	7.4

Table 7
Effect of wing type ranked by force

Type of Wing	Number Tested	Force Mean	Force SD
1. Reg Twin	30	.203	.035
2. Mini Twin	50	.174	.055
3. Mod Twin	20	.167	.051
4. Single	40	.156	.070

ported in stress units, i.e. force per unit area, whereas in orthodontic therapy, strength is frequently a force alone. This makes a larger area in orthodontic terms. This is not the case in materials engineering; strength is either the yield stress or the maximum stress prior to breaking. This is a concept quite independent of geometry.[11,12]

The two strongest materials in these brackets were 17-4PH and 303S stainless steels. Their average permanent deformation stress was 216 ksi. The 393SE, 310SS, and 316L averaged 96.6 ksi—less than half as strong (Table 5).

The force needed to permanently deform metal brackets was highest for the regular twin design. This is to be expected since a large size bracket will allow the forces to be dissipated through a greater area, thus minimizing the stress (Table 6).

As slot torque angle increased, brackets deformed with less force. Close examination of the brackets with high angles showed a reduced volume of material to resist the applied force, so the local stress was higher.

Clinical implications

Smaller, more attractive and more comfortable metal brackets can be made without compromising the force to deform if the metal brackets are made of stronger raw materials (17-4HP or 303S).

Increasing slot torque on certain brackets will allow orthodontists to achieve lingual root torque movement more efficiently and with less chair time. However, as this study indicated, this may cause metal brackets to deform with less force. Since the effect of using a stronger material on the force

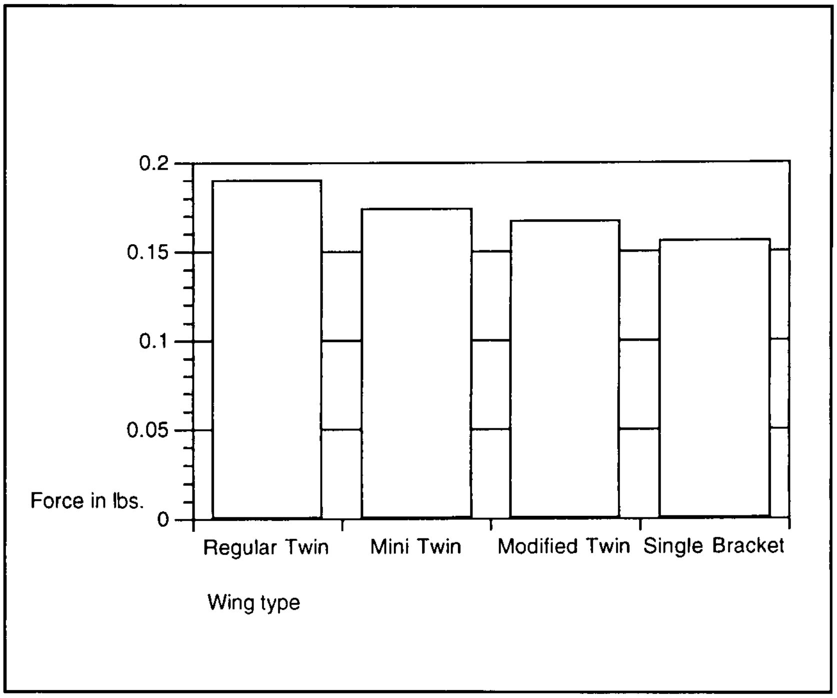

Figure 6

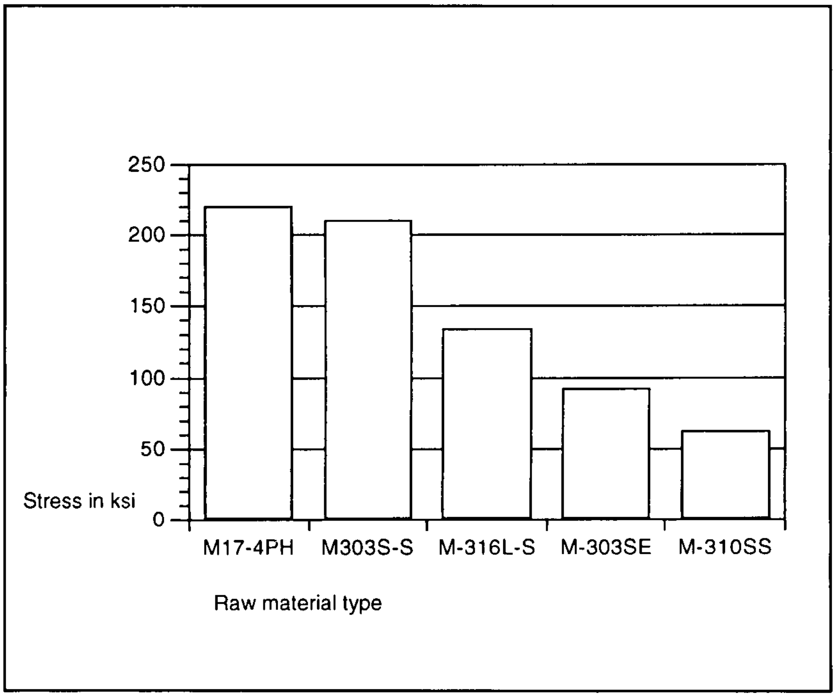

Figure 7

Figure 6
Effect of wing type on force

Figure 7
Effect of raw material on stress

needed to deform brackets is greater than that of changes in slot torque degree; it can be implied that brackets made of stronger raw materials will tolerate an increase in slot torque degree without weakening the metal brackets.

Summary

A total of 140 metal brackets, 10 each of 14 different types, were tested for the force and stress required to cause deformation. In order to separate the design and material parameters, force and stress at failure were evaluated. Each type of bracket was evaluated according to the variables of material, slot torque degree, and wing type to see if they would have a significant effect on the force and stress at failure.

Results of this investigation led to the following conclusions:

1. Raw material had a significant effect on the force needed to permanently deform metal brackets. 17-4PH and 303S had the highest yield strengths.
2. Wing type had a significant effect on the force needed to permanently deform metal brackets. Regular twin brackets had the highest resistance to deformation.
3. Slot torque had a significant effect on the force required to permanently deform metal brackets. As the slot torque degree increased the metal bracket deformed with less force.
4. Of the three variables, raw material had the greatest effect on the force needed to permanently deform metal brackets. The brackets which required the greatest stress to permanently deform were made with the steels of greatest strength, 17-4HP and 303S

One can conclude that the material parameter was the most important factor which influenced the force needed to deform metal brackets. Based on the results of this study, brackets need to be fabricated from a strong material, with enough bulk and a slot designed to prevent permanent deformation during orthodontic treatment. This information is of particular importance today, when esthetics is a main concern and, consequently, brackets are made smaller. The orthodontist may wish to choose mini-brackets made of a stronger stainless steel.

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