The Open Dentistry Journal
DOI: 10.2174/0118742106406819251013060630, 2025, 19, e18742106406819
ISSN: 1874-2106

REVIEW ARTICLE **OPEN ACCESS**

Narrative Review on Materials and Manufacturing Techniques of Metal Brackets

Çağan Erkman Şaylan[1,*]

[1]*Department of Orthodontics, Faculty of Dentistry, Kocaeli University, Kocaeli, Türkiye*

Abstract:

Introduction: The metallic materials used in orthodontic brackets, such as stainless steel, cobalt-chromium, titanium, and precious metal alloys, exhibit varying mechanical and biological properties. This review aims to evaluate the characteristics of these materials and examine the manufacturing methods employed in bracket production.

Methods: This study was designed as a narrative review. A comprehensive literature search was conducted using PubMed, Scopus, and Google Scholar. Keywords such as "metal brackets," "stainless steel," "cobalt-chromium," "titanium," "casting," "sintering," and "metal injection molding" were used. Articles focusing on material composition, mechanical performance, and manufacturing techniques were selected for synthesis.

Results: Stainless steel brackets, especially those made from austenitic and precipitation-hardened types, are widely used due to their cost-efficiency and strength. Cobalt-chromium and titanium brackets offer superior biocompatibility and corrosion resistance. Metal Injection Molding (MIM) allows for precise and efficient bracket production, reducing material waste and minimizing cytotoxicity concerns.

Conclusion: Advancements in materials and manufacturing techniques have significantly improved the performance of orthodontic brackets. MIM, titanium alloys, and biocompatible alternatives offer promising pathways for reducing allergic reactions and improving clinical outcomes.

Keywords: Bracket production, Stainless steel brackets, Titanium alloys, Corrosion resistance, Metal injection molding.

*Address correspondence to this author at the Paşadağ Mahallesi, Department of Orthodontics, Faculty of Dentistry, Akçakesme Sokak Kocaeli University, Başiskele, Kocaeli, Türkiye 41190; E-mail: saylancagan@gmail.com

Cite as: Şaylan ÇE. Narrative Review on Materials and Manufacturing Techniques of Metal Brackets. Open Dent J, 2025; 19: e18742106406819. http://dx.doi.org/10.2174/0118742106406819251013060630

Received: April 17, 2025
Revised: August 11, 2025
Accepted: September 08, 2025
Published: November 13, 2025

1. INTRODUCTION

1.1. Characteristics of Different Components in Metal Brackets

The evolution and modifications of orthodontic brackets over the years are fundamentally driven by the need for these brackets to exhibit a range of conflicting characteristics. From a mechanical standpoint, the wing of the bracket, which interfaces with the archwire, requires a high modulus of elasticity to resist undesirable plastic deformation, necessitating rigidity. Meanwhile, the slot should be fabricated from a hard alloy that minimizes wear during the movement of the wire within it. In contrast, the base of the bracket, which adheres to the enamel surface of the tooth, must be designed to permit adequate deformation to facilitate easy removal upon the completion of treatment [1].

Initially, metal brackets were crafted from various stainless steel alloys through casting and machining techniques. The base and wings of the bracket were produced either by casting or machining, and these components were assembled through soldering. More recently, advancements in manufacturing technologies, such as laser processing and Metal Injection Molding (MIM), have expanded the variety of orthodontic materials available, including titanium alloys, cobalt-chromium alloys, and gold alloys [2].

2. METHODOLOGY

This study was designed as a narrative review. A comprehensive literature search was conducted using electronic databases, including PubMed, Scopus, and Google Scholar, to identify relevant articles related to metal brackets used in orthodontics. The search terms included combinations of “metal brackets,” “orthodontics,” “stainless steel,” “cobalt-chromium,” “titanium,” “casting,” “sintering,” “metal injection molding,” and “manufacturing techniques.” Publications in English up to December 2024 were considered. Studies focusing on material composition, biomechanical properties, and manufacturing processes were included, while case reports and studies lacking detailed methodology were excluded. The selected articles were synthesized to provide a comprehensive overview of the materials and manufacturing methods used in metal orthodontic brackets.

2.1. Manufacturing Techniques

2.1.1. Casting Method

In the casting process, the components are melted. The molten alloy is poured into an appropriate mold, where it is allowed to solidify. Casting can be used for single-piece orthodontic brackets and for individually customized brackets. This method is particularly suited for creating intricate parts, such as the grids on the bracket base and the wings [3]. However, casting is a relatively expensive process because approximately 90% of the metal is lost as waste. Similarly, during machining, up to 75% of the alloy material can be wasted [4].

2.1.2. Milling Method

Milling, or machining, involves shaping a material using rotating cutting tools. This method is well-suited for the economical production of geometrically simple components, such as hooks on brackets. However, manufacturing orthodontic brackets through machining is more expensive than the Metal Injection Molding (MIM) process, as it results in 50% to 75% of the material becoming unusable during the shaping process [3]. Additionally, machining carries the potential for human error. Contemporary orthodontic metal brackets are manufactured using Computer Numerical Control (CNC) milling processes, where a single piece of metal is shaped by a computer-operated machine.

2.1.3. Sintering Method

Sintering is based on the principle of atomic diffusion. It is a method used to manufacture various components from powdered particles. In this technique, the powdered material is placed into a mold and heated to a temperature just below its melting point. This heating allows the atoms within the particles to diffuse along the boundaries, enabling them to bond together and become durable. Sintering is used in the production of brackets made from both metal and ceramic materials.

2.1.4. Soldering Method

After both components are manufactured, the wings are attached to the bracket base through a soldering process (Figs. **1** and **2**) [5-7]. In this process, an additional alloy is applied at the junction between the base and the wings. The ability to solder stainless steel is influenced by the specific elements present in the alloy. Initially, silver-based alloys were widely used for producing brackets. Unfortunately, these alloys were negatively impacted by cadmium, which was added to improve wettability and lower melting temperatures [5]. However, this combination of base and wings is prone to galvanic corrosion. This corrosion can cause the release of copper and zinc ions, which are common in silver-based filler alloys. Beyond the biocompatibility concerns, the deterioration of the hard solder alloy may cause the wings to detach from the base when the bracket is removed. To counter this issue, some manufacturers started using gold-based alloys to solder the wings to the base. Despite this, gold alloys are more cathodic compared to stainless steel. This difference results in intraoral corrosion of the bracket bases and the release of nickel, which poses potential health risks, such as allergic reactions and cytotoxic effects [6].

Nickel-based soldering alloys have been developed to address galvanic interaction concerns between different alloys. In summary, no soldering alloy available today completely satisfies all the requirements. These factors involve compatibility with stainless steel, adequate mechanical strength of the components, and a decrease in galvanic currents when used with stainless steel [4].

2.1.5. Metal Injection Molding (MIM)

MIM is a modern technique developed in the early 1980s for producing metallic components. It has been widely adopted by orthodontic material manufacturers due to its cost-effectiveness and material savings compared to traditional methods [1]. In metal injection molding, metal powders are combined with organic binders to produce a consistent mixture. It is then injected into a mold to achieve the required final shape. The initial mold is about 20% larger to account for shrinkage during the sintering stage. After molding, the debinding process removes over 90% of the organic binders using solvents, heat, or both. The final sintering step at high temperatures causes the brackets to shrink by up to 22%, achieving the desired size and over 97% of the theoretical density of the material [1]. Metal injection molding is particularly beneficial for producing orthodontic brackets, as it offers precise control over complex shapes and reduces material waste.

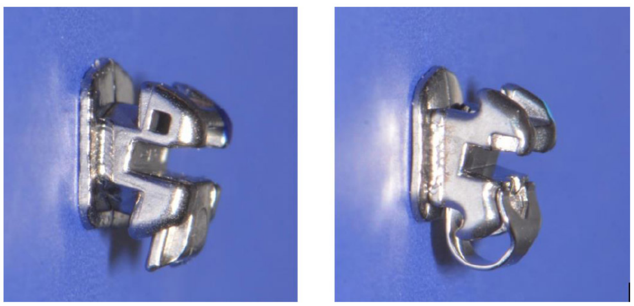

Fig. (1). Brackets with base parts joined by the soldering method [7].

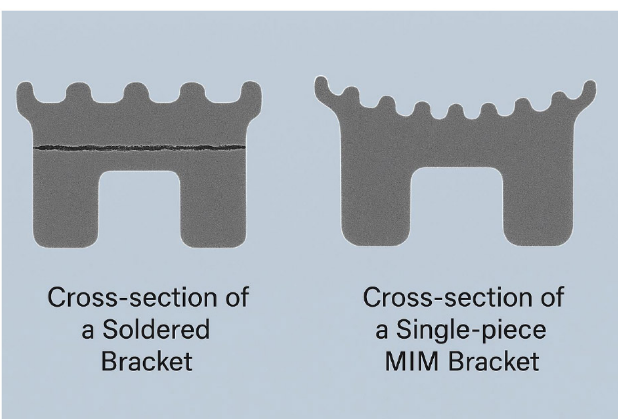

Fig. (2). Cross-sectional illustration of a soldered orthodontic bracket (left) and a single-piece MIM-manufactured bracket (right).

Orthodontic brackets traditionally manufactured from two types of stainless steel alloys (type 316 and 17-4 PH) have also been produced using the MIM method [8]. Additionally, other (iron-cobalt) chromium alloys have been utilized. MIM brackets are produced as single-piece units, eliminating the issue of galvanic current formation that is associated with soldering alloys (Figs. **2** and **3**) [7]. However, despite having similar compositions, different alloys can exhibit considerable variations in their electrochemical properties and biocompatibility.

Advantages of the MIM Method:

- Single-piece production with high precision.
- Since metal injection molding brackets do not require soldering, the risk of cytotoxicity is reduced.
- Wing detachment from the brackets during debonding does not occur with MIM brackets.
- The cost of MIM brackets is low due to minimal material waste during production.
- MIM brackets are resistant to corrosion, making them suitable for patients with nickel allergies.

Fig. (3). Metal bracket produced by the MIM method [7].

MIM brackets that undergo secondary surface treatments have smooth surfaces, resulting in low friction resistance. However, internal porosity has been observed in all commercially available metal injection molding brackets, which is believed to be related to the shrinkage that occurs in the final production stage. Porosity development is a recognized issue for metal injection molding products, negatively impacting their mechanical properties. A study has found that the hardness of MIM brackets is significantly lower than that of conventional brackets [9]. This disparity may increase the degree of wear during the activation of the archwire, particularly when using very hard stainless steel archwires. This method may also result in subtle surface irregularities that can contribute to plaque retention and localized corrosion on bracket surfaces. On the other hand, under identical bonding protocols, welded-base stainless-steel brackets showed significantly higher shear bond strength than MIM-base brackets, indicating that base manufacturing method can influence adhesion performance [10]. Across brands, most commercially available brackets exhibit slot oversizing relative to nominal dimensions, with variability attributable to manufacturing technique (casting, milling, MIM), measurement position, and batch effects [11].

3. MATERIALS USED IN METAL BRACKETS

The four primary alloys commonly employed are Stainless Steel (SS), Cobalt-Chromium (Co-Cr), Titanium (Ti), and Precious Metal alloys (PM) [12].

3.1. Effects of Some Elements in Stainless Steel Alloys

3.1.1. Chromium

Chromium is the most critical alloying element in stainless steel, providing fundamental corrosion resistance. As the chromium content increases, so does the steel's resistance to corrosion and oxidation, particularly at high temperatures. Chromium also promotes a ferritic structure. In a case-control study, patients with fixed appliances showed significantly higher urinary chromium levels in the stainless-steel archwire group compared to controls and NiTi, while nickel levels were low and not significantly different, suggesting that prolonged treatment may increase systemic Cr exposure [13].

3.1.2. Carbon

Incorporated into stainless steel to enhance hardness and durability. While a higher carbon content can increase hardness, it also poses the risk of forming chromium carbides, which may lead to localized corrosion in the presence of oral fluids.

3.1.3. Nickel

Stabilizes the austenitic phases of stainless steel. Enhances its resistance to oxidation and corrosion. In Precipitation-Hardened (PH) steels, nickel also contributes to forming intermetallic compounds that improve durability. Due to the weak bonding of nickel atoms, there is a potential risk of nickel ions being released when exposed to oral fluids. To reduce the risk of nickel hypersensitivity, it is essential to enhance the corrosion resistance of stainless steel to minimize the release of nickel ions.

3.1.4. Manganese

It is an austenite-forming element. Mn has been used as a substitute for nickel.

3.1.5. Nitrogen

Enhances the austenitic stability of stainless steel-an austenite-forming element.

3.1.6. Molybdenum

Added to increase the steel's resistance to pitting corrosion, especially from chlorides.

3.1.7. Titanium

Utilized for stabilization of carbide. Enhances the corrosion resistance.

3.1.8. Phosphorus

Helps enhance durability and corrosion resistance and lowers the sintering temperature.

3.1.9. Niobium

Added to stabilize carbon in the steel and increase its corrosion resistance.

3.1.10. Copper

Incorporated into stainless steel to impart precipitation hardening properties.

3.1.11. Selenium

Added to improve the machinability of the steel, though it reduces hardness and durability [3].

3.2. Stainless Steel Alloy

Stainless steel alloys are classified into five categories according to their microstructure and chemical composition [14]:

- Ferritic.
- Martensitic.
- Austenitic.
- Duplex (Austenitic-Ferritic).
- Precipitation-Hardening (PH).

3.2.1. Ferritic Stainless Steel

According to the American Iron and Steel Institute (AISI), ferritic stainless steels are classified under the 400 series [15]. These alloys generally contain 12% to 29% chromium and have very low nickel content, usually less than 2% (Table **1**). Due to their low nickel content, ferritic stainless steels are cost-effective. They are known for being magnetic, easy to shape, and resistant to corrosion. However, they cannot be hardened through heat treatment. Their limitations in welding and machinability reduce their applicability in dental uses. The most commonly known ferritic alloy, AISI 430, has about 17% chromium [16].

Table 1. Nickel (Ni) content in various stainless steel alloys commonly used in orthodontic brackets.

Alloy Type	AISI Series	Ni (%)
Ferritic	4** Series	<2
Martensitic	4** Series	>0,75
Austenic	3** Series	8-12
Dublex	2205 Series	4,5-6,5
Precipitation-Hardening (PH)	630(17-4) Series	3-5

3.2.2. Martensitic Stainless Steels

Martensitic stainless steels, like ferritic types, are part of the 400 series. These alloys are valued for their high strength and hardness, which is why they are often used in surgical instruments due to their ability to undergo heat treatment. However, their resistance to corrosion is generally lower, and it can further decline after heat treatment. Their workability also tends to decrease after treatment [15]. The carbon content in these alloys ranges from 0.15% to 1%, while the chromium content varies from 12% to 18%. Martensitic alloys, such as AISI 420 and

440, are commonly employed in the production of knives and cutters [16].

3.2.3. Austenitic Stainless Steels

Austenitic stainless steels are the primary materials used in the production of orthodontic brackets and wires, representing the most common type among stainless steels [15-17]. The austenitic phase is achieved when the alloy is heated above 912°C [18]. In the AISI 300 series, the addition of nickel is crucial to stabilize the face-centered cubic structure at room temperature [15, 16, 19, 20]. A minimum of 8% nickel content is required to maintain this structure, ensuring both the strength and formability of the alloy [21].

AISI 302 is a key alloy containing 17% to 19% chromium, 8% to 10% nickel (Table **1**), and 0.15% carbon. AISI 304, similarly, consists of 18% to 20% chromium, 8% to 12% nickel, and up to 0.08% carbon, and is often called 18/8 stainless steel due to its chromium and nickel composition [15]. The 316 alloy is another version of 18/8 stainless steel, with added molybdenum to enhance resistance to pitting corrosion. Later, the carbon content in 316 alloy was reduced to a maximum of 0.03% to further improve corrosion resistance and reduce sensitivity. This low-carbon version is known as 316L, where "L" denotes low carbon. Similarly, 304L contains 18% to 20% chromium, 8% to 10% nickel, less than 0.03% carbon, and small amounts of manganese and silicon [18]. Other types of austenitic stainless steels are mostly not utilized in orthodontic applications.

Austenitic stainless steels are well-known for their high resistance to corrosion. They also offer good formability, weldability, and resistance to wear [16]. However, these alloys cannot be hardened through heat treatment. This is because their phase transitions occur at temperatures lower than what is required for atomic diffusion. Consequently, austenitic stainless steels are suitable for applications that do not need heat hardening, such as wires and non-cutting instruments [19]. Despite their advantages, these alloys can still suffer from intergranular corrosion and stress corrosion cracking [22].

The 200 series, developed in the 1930s in response to nickel shortages and high prices, contains low nickel content. To maintain an austenitic structure, the nickel content was reduced, and manganese and nitrogen were added, although these alloys still contain some nickel. The chromium content was also reduced, leading to lower corrosion resistance than the standard 300 series [17]. Despite being cheaper than the 300 series, the use of these alloys in dentistry has not been reported [15].

3.2.4. Duplex Stainless Steels (Austenitic-Ferritic)

The microstructure of this alloy comprises a combination of austenitic and delta-ferritic phases [23, 24]. It features a high chromium content (18% to 26%) and a low nickel content (4% to 7%) (Table **1**), with most variants containing 2% to 3% molybdenum. The most commonly used grade is AISI 2205 [24].

Duplex stainless steels are known for their good weldability, as well as their higher tensile strength and resistance to plastic deformation compared to austenitic or ferritic stainless steels [25]. They are harder than austenitic types while being more formable than ferritic types. Due to the presence of the austenitic phase, duplex stainless steels exhibit good corrosion resistance [24]. Studies have shown that duplex alloys offer superior corrosion resistance compared to austenitic types [22].

3.2.5. Precipitation-Hardening (PH) Stainless Steels

The development and use of this type of alloy have been ongoing since 1946 [26]. It typically contains 15.50% to 17.50% chromium, 3% to 5% nickel (Table **1**), and 0.07% carbon. It also includes 3% to 5% copper, along with smaller quantities of manganese, silicon, phosphorus, and sulfur [27]. A well-known example is AISI 630, or 17-4 PH, which is a martensitic alloy. This alloy is enhanced through precipitation hardening and is commonly applied in various industries, such as medicine and dentistry [28]. This semi-austenitic stainless steel is highly formable and can be hardened by transforming from the austenitic phase to the martensitic phase [26]. It offers corrosion resistance equal to or better than type 304 stainless steel and has high strength, but its significant hardness makes it challenging to machine [28].

3.2.6. Super Stainless Steels

While austenitic stainless steels are the preferred alloys for orthodontic applications, there are concerns within the orthodontic community regarding the potential for nickel-induced allergic reactions. Additionally, there is a growing demand from clinicians for alloys that offer superior corrosion resistance, enhanced strength, and better formability. To meet these needs, super austenitic stainless steel, known as SR-50a, has been developed. This alloy creates a passive film layer due to its high nitrogen (0.331%) and molybdenum (6.77%) content, providing corrosion resistance that is comparable to that of titanium components [18, 29]. SR-50a has been experimentally tested in the production of orthodontic brackets and wires, showing promising results [18, 29, 30].

Several metal alloys, including 303, 304, 316, and 17-4 PH, are utilized in manufacturing the wing and base components of stainless steel brackets. Among these, 17-4 PH stainless steel is preferred for orthodontic brackets due to its significantly superior mechanical properties compared to 303, 304, and 316/316L austenitic stainless steels, making it more effective in controlling tooth movement [4]. However, both 304 and 17-4 PH stainless steels are known to have low corrosion resistance when exposed to chloride solutions [18].

Biocompatibility is closely associated with corrosion properties, which is why the corrosion behavior of orthodontic alloys in the oral environment and the potential allergic reactions to nickel in some patients have been extensively studied [31, 32]. The nickel-free AISI 2205 stainless steel alloy, featuring both austenite and ferrite in its microstructure, has also been used in the production of brackets. In materials engineering, AISI 2205 is valued for its greater hardness and improved corrosion resistance compared to conventional austenitic stainless steels [24].

Table 2. Summary of metal bracket materials, manufacturing techniques, advantages, and disadvantages.

Bracket Material	Key Properties & Advantages	Limitations / Disadvantages
Stainless Steel (*e.g.*, 304L, 316L, 17-4 PH)	High strength and form stability; corrosion resistance (especially 316L); cost-effective; easily machinable; PH types offer superior strength.	Nickel ion release (in austenitic types); potential for galvanic corrosion with soldering; PH types are difficult to machine.
Cobalt-Chromium Alloys	Excellent biocompatibility; reduced nickel content; high wear and corrosion resistance; preferred for nickel-sensitive patients.	Higher friction than titanium against certain wires; more expensive than stainless steel; limited availability; alloy variability.
Titanium & Titanium Alloys (*e.g.*, Ti-6Al-4V, Grade 2/4 CP)	Superior biocompatibility and corrosion resistance; low allergic potential; alpha-beta alloys offer greater durability; CP titanium ensures a safe bonding base.	Lower hardness (especially Grade 2 CP); vanadium ion release (Ti-6Al-4V); internal porosity with MIM; costlier than SS.
Precious Metal-Coated Alloys (*e.g.*, Gold-Plated Steel)	High aesthetic value; biologically inert surfaces (*e.g.*, gold); traditionally used in lingual systems; reduced surface reactivity.	Very high cost; limited mechanical benefits over modern SS; may require special handling; not widely available.

The 300 series (304L, 316, and 316L) austenitic stainless steels are frequently chosen for orthodontic bracket manufacturing due to their low cost, ductility, and corrosion resistance(Table **2**). The 316 series stainless steel, in particular, is often used for bracket bases because of its high corrosion resistance and low nickel release properties [33].

17-4 PH stainless steel is commonly used for the wing parts of brackets and mini brackets due to its harder structure compared to austenitic stainless steels. Although it contains a small amount of nickel, its relatively low corrosion resistance can lead to nickel release, which is considered a disadvantage [34].

Notably, 2205 stainless steels are twice as strong, more corrosion-resistant, and contain less nickel than austenitic stainless steels. Therefore, these types of brackets may be preferred for patients who are sensitive to nickel.

In an appliance-level model immersed in artificial saliva, neutral pH conditions resulted in minimal nickel release, whereas acidic conditions (pH 5) caused the highest cumulative nickel release over 168 hours, highlighting the importance of controlling dietary and chemical acidity [35].

Today, brackets produced by major companies are coded based on their content and often according to the country in which they are manufactured. While the AISI code is generally used for American-made brackets, the DIN (German Institute for Standardization; Deutsches Institut für Normung) reference is used for German-made brackets.

3.3. Chromium-cobalt Alloy

Chromium-cobalt brackets were introduced as an alternative to stainless steel brackets in the mid-1990s. These brackets can be manufactured using casting or metal injection molding techniques [36]. Cobalt-based alloys are categorized into three types: wear-resistant alloys, high-temperature alloys, and corrosion-resistant alloys [37].

Currently, cobalt-based wear-resistant alloys are utilized in the production of orthodontic brackets. In these alloys, the nickel content is kept low, typically up to a maximum of 0.5% [37], while the chromium content ranges from 25% to 30% [3]. Cobalt-chromium brackets produce lower friction than stainless steel brackets when used with stainless steel wires. On the other hand, when paired with either stainless steel or beta titanium wires, cobalt-chromium brackets result in higher friction than titanium brackets (Table **2**). An increase in chromium content in cobalt-chromium brackets reduces the risk of corrosion [38].

3.4. Titanium Alloy

In recent years, concerns have grown within orthodontics and the biomedical literature regarding the release of metal ions from orthodontic appliances and the potential biological impacts of this release [39]. Particular attention has been paid to the biocompatibility of materials. In response, some manufacturers have developed brackets made from Commercially Pure (CP) titanium and titanium alloys, known for their proven biocompatibility, excellent corrosion resistance (Table **2**), and favorable mechanical properties [40, 41].

From a materials science perspective, titanium is classified into three types:

α Titanium: Represents commercially pure (CP) unalloyed titanium.

β Titanium: Contains the Ti-15V-3Cr-3Sn-3Al alloy.

α and β Titanium: Includes the Ti-6Al-4V alloy.

Alloyed titanium typically provides greater durability compared to pure titanium. Commercially pure titanium is categorized into four different grades, which depend on its level of purity and the oxygen content present in the titanium. Grade 1 CP titanium possesses the highest purity, excellent corrosion resistance, and great formability. However, it also has the lowest durability among the CP titanium grades. In contrast, Grade 4 CP titanium offers the highest level of durability but has only moderate formability [3].

Currently, titanium brackets are manufactured using either Grade 2 or Grade 4 alpha titanium, or alpha-beta titanium alloy (Ti-6Al-4V). Grade 2 CP titanium, known for its lower durability, is typically used for creating the base of the bracket. On the other hand, the wing component is constructed from the much harder alpha-beta titanium alloy, Ti-6Al-4V [40, 42]. These two parts are then joined using laser technology to create a single bracket unit. In clinical practice, it is crucial to combine the harder slot and wing parts with a softer base, similar to the method used with stainless steel brackets. The softer base makes it easier to remove the bracket from the tooth at the end of treatment. The harder slot and wing components are important for effectively transferring torque forces to the tooth. Due to potential biological concerns related to the release of vanadium from Ti-6Al-4V titanium alloy, some manufacturers have started using Grade 4 CP titanium for brackets. These brackets are made through milling or metal injection molding processes [42].

3.5. Precious Metal Alloy

Brackets made from precious metals are usually steel brackets coated with metals such as gold, platinum, or palladium [43]. Among these, gold-plated brackets in 16, 18, and 24 carats are commonly used in lingual orthodontics. Gold has been a preferred material in various dental applications due to its inert properties. Initially, the first edgewise brackets were constructed from gold. However, as time passed, stainless steel brackets became more favored due to the high cost of gold (Table **2**).

3.6. Customized Orthodontic Brackets

A recent comprehensive review suggests CAD/CAM and 3D-printed customized bracket systems can improve slot precision and may reduce treatment time and cost, although current evidence remains heterogeneous and material-dependent [44]. Despite the growing interest in in-office designing and 3D printing of customized orthodontic brackets, using either bracket resin or ceramic materials such as zirconia, the clinical reality still presents considerable limitations. As Panayi (2023) pointed out, while the mechanical customization of such brackets is rapidly evolving, their biological behavior remains largely unpredictable [45]. Furthermore, concerns about long-term durability, stress-handling, and biocompatibility under intraoral conditions persist. In contrast, metal brackets-especially those produced using advanced manufacturing techniques like metal injection molding or CNC milling-continue to demonstrate superior mechanical stability, consistent force delivery, and well-documented biological response (Table **2**). Comparative testing found the lowest friction with stainless-steel bracket + stainless-steel wire combinations, and the highest with ceramic brackets paired with NiTi wires; self-ligating brackets showed intermediate values [46]. For these reasons, metal brackets remain the gold standard in fixed orthodontic treatment, particularly in cases where efficiency and reliability are paramount.

4. RESULTS

The development and production of metal orthodontic brackets involve a diverse range of materials and manufacturing techniques, each offering specific advantages and limitations. Stainless steel remains the most commonly used material due to its favorable balance of cost, strength, and corrosion resistance. However, advancements in materials such as titanium and cobalt-chromium alloys have introduced alternatives that respond to growing concerns about biocompatibility and nickel hypersensitivity. Likewise, manufacturing innovations such as metal injection molding (MIM) have revolutionized bracket fabrication by offering greater precision, reduced material waste, and improved structural integrity.

CONCLUSION

In summary, both material selection and production methods play a pivotal role in the clinical performance and biocompatibility of orthodontic brackets. The continued evolution of bracket systems depends not only on enhancing mechanical properties but also on minimizing adverse biological reactions. Emerging technologies and material science will likely drive further improvements, contributing to safer, more effective, and patient-specific orthodontic solutions.

AUTHOR'S CONTRIBUTIONS

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

LIST OF ABBREVIATIONS

MIM	=	Metal Injection Molding
PH	=	Precipitation-Hardening
SS	=	Stainless Steel
Co-Cr	=	Cobalt-Chromium
CP Ti	=	Commercially Pure Titanium
AISI	=	American Iron and Steel Institute
CNC	=	Computer Numerical Control

CONSENT FOR PUBLICATION

Not applicable.

FUNDING

None.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

ACKNOWLEDGEMENTS

Declared none.

REFERENCES

[1] Eliades T, Zinelis S, Bourauel C, Eliades G. Manufacturing of orthodontic brackets: A review of metallurgical perspectives and applications. Recent Pat Mater Sci 2008; 1(2): 135-9. http://dx.doi.org/10.2174/1874464810801020135

[2] Zinelis S, Sifakakis I, Katsaros C, Eliades T. Microstructural and mechanical characterization of contemporary lingual orthodontic brackets. Eur J Orthod 2014; 36(4): 389-93. http://dx.doi.org/10.1093/ejo/cjt086 PMID: 24232131

[3] Khan H. Orthodontic brackets Sel Place Debonding. North Charleston: SC Creat 2015.

[4] Iijima M, Zinelis S, Papageorgiou SN, Brantley W, Eliades T. Orthodontic brackets. In: Eliades T, Brantley WA, Eds. Orthodontic Applications of Biomaterials. Woodhead Publishing 2017; pp. 75-96. http://dx.doi.org/10.1016/B978-0-08-100383-1.00004-7

[5] Maijer R, Smith DC. Corrosion of orthodontic bracket bases. Am J

Orthod 1982; 81(1): 43-8.
http://dx.doi.org/10.1016/0002-9416(82)90287-1 PMID: 6758590

[6] Wataha JC, Malcolm CT, Hanks CT. Correlation between cytotoxicity and the nlms released by dental casting alloys. Int J Prosthodont 1995; 8(1): 9-14.
PMID: 7710632

[7] Şaylan ÇE, Özel MB. Compressive strength comparison of different orthodontic metal bracket systems. Appl Sci 2024; 14(15): 6692.
http://dx.doi.org/10.3390/app14156692

[8] Zinelis S, Annousaki O, Makou M, Eliades T. Metallurgical characterization of orthodontic brackets produced by Metal Injection Molding (MIM). Angle Orthod 2005; 75(6): 1024-31.
http://dx.doi.org/10.1043/0003-3219(2005)75[1024:MCOOBP]2.0.CO;2 PMID: 16448250

[9] Zinelis S, Al Jabbari YS, Gaintantzopoulou M, Eliades G, Eliades T. Mechanical properties of orthodontic wires derived by instrumented indentation testing (IIT) according to ISO 14577. Prog Orthod 2015; 16(1): 19.
http://dx.doi.org/10.1186/s40510-015-0091-z PMID: 26089176

[10] Izquierdo LAV, Sanches FSH, Molina F, Henriques RP, Cruz EF, Freitas KMS. Comparative study of adhesion of brackets with Metal Injection Molding (MIM) technology and welded bases: *In vitro* study. Open Dent J 2020; 14: 14-240.
http://dx.doi.org/10.2174/1874210602014010240

[11] Nahidh M, Yassir YA. Evaluating orthodontic bracket slot dimensions and morphology: A narrative review. J Orthod Sci 2023; 12(1): 40.
http://dx.doi.org/10.4103/jos.jos_39_23 PMID: 37881671

[12] Brantley W, Berzins D, Iijima M, Tufekçi E, Cai Z. Structure/property relationships in orthodontic alloys. In: Eliades T, Brantley WA, Eds. Orthodontic Applications of Biomaterials. Woodhead Publishing 2017; pp. 3-38.
http://dx.doi.org/10.1016/B978-0-08-100383-1.00001-1

[13] Al-Rawe RA, Al-Zubaydi FS, Nahidh M, Alsheekhly B. Urinary nickel and chromium levels in orthodontic patients: A case-control study. J Orthod Sci 2025; 14(1): 21.
http://dx.doi.org/10.4103/jos.jos_131_24 PMID: 40630782

[14] Yoo YR, Jang SG, Oh KT, Kim JG, Kim YS. Influences of passivating nlms on the corrosion and biocompatibility of super stainless steels. J Biomed Mater Res B Appl Biomater 2008; 86B(2): 310-20.
http://dx.doi.org/10.1002/jbm.b.31018 PMID: 18161790

[15] Anusavice KJ. PHILLIPS Ciencia de los materiales dentales. Elsevier Espana 2004.

[16] Padilla ED. Aplicaciones de los aceros inoxidables. Rev Inst Investig Fac Minas Metal Cienc Geográficas 1999; 2: 11-22.

[17] Izquierdo PP, de Biasi RS, Elias CN, Nojima LI. Martensitic transformation of austenitic stainless steel orthodontic wires during intraoral exposure. Am J Orthod Dentofacial Orthop 2010; 138(6): 714.e1-5.
http://dx.doi.org/10.1016/j.ajodo.2010.05.015 PMID: 21130328

[18] Oh KT, Choo SU, Kim KM, Kim KN. A stainless steel bracket for orthodontic application. Eur J Orthod 2005; 27(3): 237-44.
http://dx.doi.org/10.1093/ejo/cji005 PMID: 15947222

[19] McCabe JF, Walls AW. Applied Dental Materials. John Wiley & Sons 2013.

[20] Park JB, Kim YK. Metallic biomaterials. In: Park JB, Kim YK, Eds. Biomaterials. Boca Raton: CRC press 2007; pp. 1-1.

[21] Coates G, Cutler P. Nickel-containing stainless steels: This article is the Introduction to The Nickel Advantage, a-50-page citation replete with useful information about the physical and mechanical properties, weldability, and corrosion resistance of nickel-containing stainless steels. Adv Mater Process 2009; 167: 29-33.

[22] Cobb HM. The history of stainless steel. ASM International 2010.
http://dx.doi.org/10.31399/asm.tb.hss.9781627083560

[23] Cardarelli F. Magnetic materials. Materials Handbook: A Concise Desktop Reference. London: Springer 2008; pp. 487-517.

[24] Platt JA, Guzman A, Zuccari A, *et al.* Corrosion behavior of 2205 duplex stainless steel. Am J Orthod Dentofacial Orthop 1997; 112(1): 69-79.
http://dx.doi.org/10.1016/S0889-5406(97)70276-2 PMID: 9228844

[25] Chai G, Soderman A, Etheridge P. High and super high strength duplex stainless steels for wire applications. Stainl Steel World 2007; 19-23.

[26] Craig RG, Slesnick HJ, Peyton FA. Application of 17-7 precipitation-hardenable stainless steel in dentistry. J Dent Res 1965; 44(3): 587-95.
http://dx.doi.org/10.1177/00220345650440032401 PMID: 14304297

[27] Craig HL. Stress Corrosion-New Approaches. ASTM International 1976; Vol. 610.
http://dx.doi.org/10.1520/STP610-EB

[28] Marques RA, Saliba-Silva AM, Rogero SO, Montemor M de F, Costa I. A comparative study of the corrosion resistance of stainless steels obtained by powder metallurgy techniques for application in dental prosthesis. Materials Science Forum. 660: 617-22.
http://dx.doi.org/10.4028/www.scientific.net/MSF.660-661.617

[29] Oh KT, Kim YS, Park YS, Kim KN. Properties of super stainless steels for orthodontic applications. J Biomed Mater Res B Appl Biomater 2004; 69B(2): 183-94.
http://dx.doi.org/10.1002/jbm.b.30002 PMID: 15116408

[30] Oh KT, Hwang CJ, Park YS, Kim KN. *In vitro* corrosion resistance of orthodontic super stainless steel wire: The effects of stress relieving heat-treatment. J Electrochem Soc 2002; 149(9): B414.
http://dx.doi.org/10.1149/1.1497983

[31] Menezes LM, Campos LC, Quintão CC, Bolognese AM. Hypersensitivity to metals in orthodontics. Am J Orthod Dentofacial Orthop 2004; 126(1): 58-64.
http://dx.doi.org/10.1016/j.ajodo.2003.05.014 PMID: 15224060

[32] Faccioni F, Franceschetti P, Cerpelloni M, Fracasso ME. *In vivo* study on metal release from fixed orthodontic appliances and DNA damage in oral mucosa cells. Am J Orthod Dentofacial Orthop 2003; 124(6): 687-93.
http://dx.doi.org/10.1016/j.ajodo.2003.09.010 PMID: 14666083

[33] Matasa CG. Characterization of used orthodontic brackets. Dental Materials In Vivo: Aging and Related Phenomena. New York, NY: Quintessence Publishing 2003; pp. 141-56.

[34] Flores DA, Choi LK, Caruso JM, Tomlinson JL, Scott GE, Jeiroudi MT. Deformation of metal brackets: A comparative study. Angle Orthod 1994; 64(4): 283-90.
http://dx.doi.org/10.1043/0003-3219(1994)064<0283:DOMBAC>2.0.CO;2 PMID: 7978523

[35] Ouédraogo Y, Sakira AK, Ouédraogo M, Tapsoba I, Konsem T, Beugré JB. Influence of pH on the release of nickel ions from fixed orthodontic appliances in artificial saliva. J Orthod Sci 2024; 13(1): 49.
http://dx.doi.org/10.4103/jos.jos_8_24 PMID: 39758112

[36] Eliades T, Brantley WA. Orthodontic applications of Biomaterials: a clinical guide. Woodhead Publishing 2016.

[37] Haddad ACSS, Tortamano A, Souza AL, Oliveira PV. An *in vitro* comparison of nickel and chromium release from brackets. Braz Oral Res 2009; 23(4): 399-406.
http://dx.doi.org/10.1590/S1806-83242009000400009 PMID: 20027447

[38] Nair S, Padmanabhan R, Janardhanam P. Evaluation of the effect of bracket and archwire composition on frictional forces in the buccal segments. Indian J Dent Res 2012; 23(2): 203-8.
http://dx.doi.org/10.4103/0970-9290.100426 PMID: 22945710

[39] Marcusson JA, Lindh G, Evengård B. Chronic fatigue syndrome and nickel allergy. Contact Dermat 1999; 40(5): 269-72.
http://dx.doi.org/10.1111/j.1600-0536.1999.tb06061.x PMID: 10344482

[40] Zinelis S, Annousaki O, Eliades T, Makou M. Metallographic structure and hardness of titanium orthodontic brackets. J Orofac Orthop 2003; 64(6): 426-33.
http://dx.doi.org/10.1007/s00056-003-0308-5 PMID: 14628134

[41] Darabara MS, Bourithis LI, Zinelis S, Papadimitriou GD. Metallurgical characterization, galvanic corrosion, and ionic release of orthodontic brackets coupled with Ni-Ti archwires. J

Biomed Mater Res B Appl Biomater 2007; 81B(1): 126-34.
http://dx.doi.org/10.1002/jbm.b.30645 PMID: 16969817

[42] Gioka C, Bourauel C, Zinelis S, Eliades T, Silikas N, Eliades G. Titanium orthodontic brackets: Structure, composition, hardness and ionic release. Dent Mater 2004; 20(7): 693-700.
http://dx.doi.org/10.1016/j.dental.2004.02.008 PMID: 15236945

[43] Eliades T, Athanasiou AE. *In vivo* aging of orthodontic alloys: Implications for corrosion potential, nickel release, and biocompatibility. Angle Orthod 2002; 72(3): 222-37.
http://dx.doi.org/10.1043/0003-3219(2002)0720222:IVAOOA>2.0.CO;2 PMID: 12071606

[44] Elabed I, Zheng Z, Zhang Y, Chung CH, Li C. The mechanical and clinical properties of customized orthodontic bracket systems-A Comprehensive review. J Funct Biomater 2024; 15(10): 299.
http://dx.doi.org/10.3390/jfb15100299 PMID: 39452597

[45] Panayi NC. 3D printing of in office custom-made brackets: Concept, design, production and evidence. Semin Orthod 2023; 29(1): 11-6.
http://dx.doi.org/10.1053/j.sodo.2022.12.006

[46] Dubey S, Tiwari SK, Kaur L, Dubey SK, Sahoo N, Dash BP. Comparison of frictional resistance in different orthodontic wire and bracket combination. J Pharm Bioallied Sci 2025; 17(Suppl. 2): S1304-6.
http://dx.doi.org/10.4103/jpbs.jpbs_1922_24 PMID: 40655785