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Comparative Finite Element Investigation of AISI 1005, AISI 1065, and a Hybrid Friction-Welded AISI 1005–1065 Bar under Tensile, Torsional, and Combined Loading

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مقارنة باستخدام طريقة العناصر المحددة بين صلب *AISI 1005* و *AISI 1065* ووصلة هجينة من المعدنيين ملحومة بلحام الاحتكاك *AISI 1005–1065* تحت أحمال الشد والالتواء والأحمال المركبة

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Abstract:
We provide a detailed finite element analysis (FEA) focusing on the mechanical properties of low-carbon steel—AISI 1005; high-carbon steel—AISI 1065; and hybrid friction-welded specimens made from AISI 1005 and AISI 1065. In this study, we utilized SolidWorks Simulation to develop Our goal was to compare how unwelded and friction-welded configurations respond structurally, while also evaluating the feasibility of joining different carbon steels using this welding method. We defined the material properties based on standard steel grades and applied the same loading conditions across all models. The simulation results revealed that This investigation revealed that AISI 1065 steel boasts a higher tensile strength, while the friction-welded specimens show enhanced torsional resistance and a more effective load transfer through the weld interface. The hybrid specimen demonstrated a mechanical response that fell somewhere in between the parent materials, and it maintained its structural integrity regardless of the multiaxial loading conditions. The results obtained confirm that friction welding can indeed be used to create hybrid structural elements from both low- and high-carbon steels, showcasing the improved properties we've identified.

Keywords: AISI 1005, AISI 1065, Friction Welding, Finite Element Analysis, Tensile Loading, Torsional Loading, Hybrid Steel Components, SolidWorks Simulation.

الملخص
تقوم هذه الدراسة بتحليل باستخدام طريقة العناصر المحددة (Finite Element Analysis, FEA) لدراسة السلوك الميكانيكي لصلب منخفض الكربون (AISI 1005) ، وصلب عالي الكربون (AISI 1065) ، بالإضافة إلى عينة مصنوعة من هذين النوعين ملحومتين بتقنية اللحام الاحتكاكي، يتم تطبيق أحمال مختلفة مثل الشد، والالتواء، والأحمال المركبة (الشد والالتواء) على هذه العينات، تم استخدام برنامج SolidWorks Simulation لتنفيذ عمليات المحاكاة العددية ، الهدف من الدراسة هو مقارنة كيفية تصرف العينات غير الملحومة مقارنة بالعينات الملحومة، والتحقق من فعالية تقنية اللحام الاحتكاكي في ربط أنواع مختلفة من الفولاذ، تم تحديد الخصائص الميكانيكية للمواد بناءً على المعايير الخاصة بكل درجة من الفولاذ، كما تم تطبيق نفس ظروف التحميل على جميع النماذج لضمان المقارنة العادلة.

أظهرت نتائج المحاكاة أن فولاذ AISI 1065 يتمتع بمقاومة شد أعلى مقارنة بفولاذ AISI 1005 أما العينات الملحومة بالاحتكاكي، فقد أظهرت مقاومة جيدة لعزوم الالتواء، بالإضافة إلى كفاءة في نقل الأحمال من خلال منطقة اللحام ، كما أظهرت العينة الهجينة استجابة ميكانيكية متوسطة بين خصائص المادتين، مع الحفاظ على سلامتها الإنشائية تحت أنواع مختلفة من الأحمال متعددة الاتجاهات تدل النتائج على إمكانية استخدام تقنية اللحام الاحتكاكي لإنشاء عناصر هجينة تجمع بين الفولاذ منخفض الكربون والفولاذ عالي الكربون، مما يحقق خصائص ميكانيكية أفضل ويقدم حلاً عمليًا للاستخدامات الهندسية التي تحتاج إلى خليط من المتانة والصلابة والكفاءة.

الكلمات المفتاحية: AISI 1005، AISI 1065، اللحام الاحتكاكي، تحليل العناصر المحددة، أحمال الشد، أحمال الالتواء، المكونات الهجينة، المحاكاة باستخدام برنامج السولدورك.

1. Introduction

Carbon steels are a choice for mechanical and structural work. The reason is simple: by changing the amount of carbon and how the steel is processed we can adjust the steel's strength and other traits. When we add carbon we get higher yield strength, tensile strength, hardness and wear resistance. The trade-off is lower ductility, toughness and weldability. For example, low-carbon steel such as AISI 1005 is well known for its formability and weldability. In contrast high-carbon steel such as AISI 1065 gives strength and hardness yet it loses some ductility. These differences mean that it is vital to compare low-carbon steel and high-carbon steel when selecting materials for parts that will experience loads [1,3,5].

The growing demand for light strong structures has increased the use of parts made from metals. By making metal structures we can use the best features of each metal letting different parts of a piece work together for better strength. In this situation joining AISI 1005 and AISI 1065 is a chance to combine the great ductility and weldability of low-carbon steel with the high strength and hardness of high-carbon steel. The success of these hybrid parts depends largely on how well the joining process can transfer load between the two metals [8,12].

Friction welding is a joining method that makes heat by rubbing the pieces together. The pieces do not melt; instead, pressure creates a metal bond. This technique has an advantage over normal fusion welding because it reduces defects such as porosity and cracks that happen when metal melts and solidifies. It also leaves a heat-affected zone. Because of these benefits friction welding is used in fields, such as aerospace, automotive and railway engineering, where reliable joints are needed. Rotary friction welding has also been studied for joining steels, which is especially relevant for the AISI 1005 and AISI 1065 pair used in this research [14,9,6,17,4,16].

Finite Element Analysis or FEA is a computer method that helps us see how parts and welded assemblies behave under force. FEA lets us estimate stress, strain, deformation and how loads move when we set loading and boundary conditions. This gives us information before we do real tests. Earlier studies have looked at the response of carbon-steel friction-welded joints and at modeling welded parts. Software such as SolidWorks Simulation provides tools for examining stress patterns in three-dimensional models. The literature does not fully compare the numerical behavior of non-welded low-carbon steel and high-carbon steel especially when we study dissimilar friction-welded hybrids under different loading modes [12,18,19].

This study uses element simulations for particular loading and material settings but it does not test the predictions in real life. Therefore, we need a detailed numerical comparison of AISI 1005 AISI 1065 and a friction-welded AISI 1005–AISI 1065 hybrid when they are loaded in tension, torsion and combined tension-torsion. The aim is to use SolidWorks Simulation to look at and compare the stress and deformation of these three setups under the loads. We will focus on how stress spreads, how load moves across the welded joint and which areas may have stress. In the end this study will judge whether rotary friction welding can make hybrid parts from low-carbon steel and high-carbon steel. It will explain how these parts react when they face single or combined loads.

In the future research could improve the study by adding real tests looking at residual stresses, from welding studying heat effects and examining more loading conditions and different friction-welding settings.

2. Methodology

The overall approach taken in this study is visually represented in Figure 1. The steps include choosing AISI 1005 and AISI 1065 steels, figuring out the specimen shape, creating the design for the friction-welded hybrid joint, defining the material properties, applying the loading conditions, and ultimately performing a finite element analysis for comparison.

2.1 Materials

In this experiment we picked three steel bar specimens to see how carbon content and Rotary Friction Welding (RFW) change how steel bars act under tensile and torsion loads. Our steel bar specimens consist of low-carbon steel AISI 1005 unwelded high-carbon steel AISI 1065 and one hybrid joint. We chose both low-carbon steel and high-carbon steel because we want to show how different they behave.[7,17].

We made the AISI 1005-1065 specimen using Rotary Friction Welding (RFW) technology. People like using Rotary Friction Welding (RFW) because it makes good welds, with almost no tiny flaws, which makes the joints very strong. [15,13]. By looking at how the three steel bar specimens act we can find out the ways the steel bar specimens spread out stress and react to torsion and tension loads. [11].

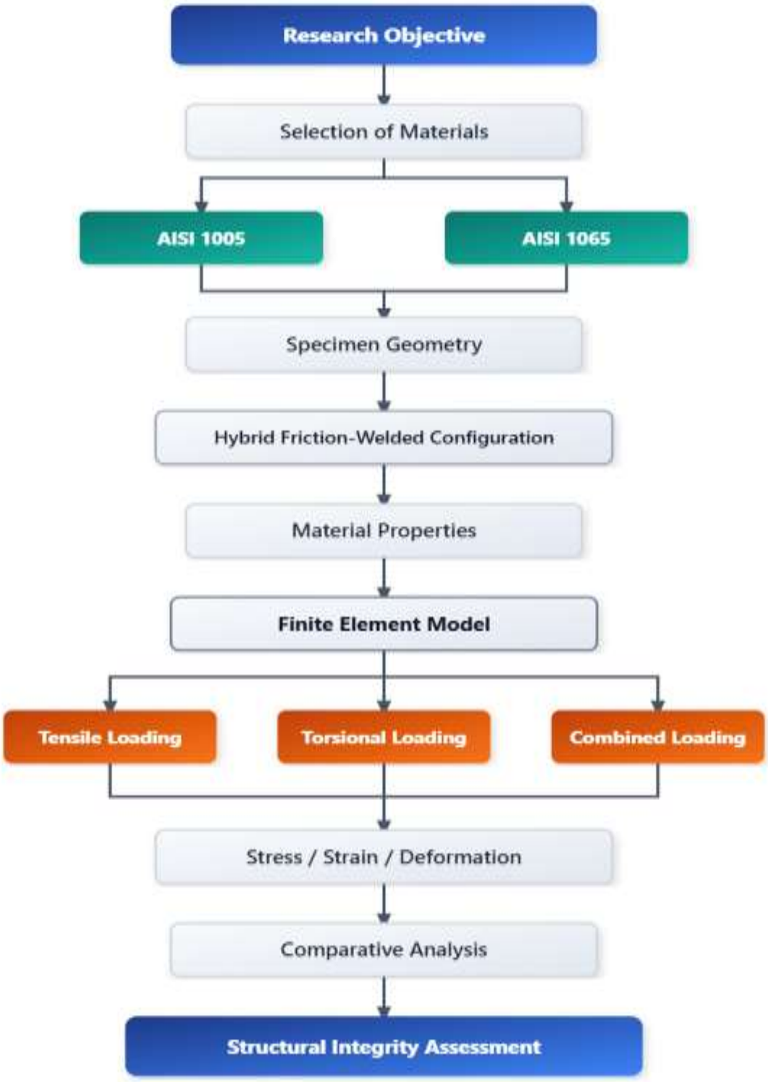

Figure 1. Schematic diagram of the research methodology

2.2 Geometry

A geometric model was created for the specimens that were discussed before. The main goal of this model was to make sure the analysis was accurate and to avoid any changes in shape that could happen when both pushing and twisting forces are applied together. The model had a solid cylinder bar. This bar was good enough for studying both pushing and twisting forces. It also allowed a clear look at the stresses that happen inside.

For the specimen the shape was made using two different metals, AISI 1005 and AISI 1065. These two metals were connected at a straight line. This is described in a study by [15]. The cylindrical model has a diameter of 150 mm and is 5.0 meters long, for the parts that are not welded. These parts can be either AISI 1005 or AISI 1065. The entire length is made from one material.

For the welded version the total length was split equally between the two metals. Each part was 2.5 meters long. The way the two steel parts were joined together by friction welding is shown in Figure 2.

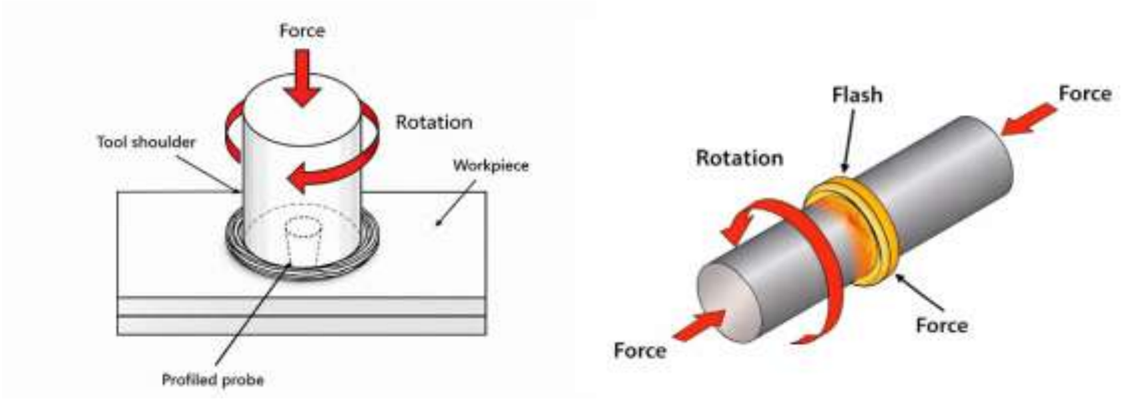

Figure 2. Schematic illustration of the friction welding mechanism

2.3 Material Properties

Table 2 presents the precise numerical values that were input into the simulation software (SolidWorks Simulation) for both AISI 1005 and AISI 1065 steel alloys.

Table 2: material properties

Property	AISI 1005	AISI 1065
Elastic Modulus (Pa)	2.10×10^{11}	2.00×10^{11}
Poisson Ratio	0.28	0.28
Density (kg/m³)	7800	7850
Yield Strength (Pa)	4.80×10^{8}	4.90×10^{8}
Ultimate Tensile Strength (Pa)	6.00×10^{8}	6.35×10^{8}

2.4 Loading Conditions

To understand how the structures work and how forces move through a friction welding joint we studied three models. These models were the two metals that were joined together (AISI 1005 and AISI 1065). The metal that was formed after the weld. For each of these three parts we did three calculations. These calculations were meant to show ways the structure might fail. The types of failure we looked at were Tensile Loading, Torsional Loading and Combined Tensile–Torsional Loading.

2.5 Governing Equations

We used the ideas of elasticity theory and solid mechanics to find the normal stress (σ) shear stress (τ) and axial strain (ε) using math formulas. This way of working helped us check if things were safe and helped us see how the loads move around. [2].

- **Normal Stress:**

$$\sigma = \frac{P}{A} \quad (1)$$

where P Is the applied tensile force and A is the cross-sectional area of the specimen.

- **Shear stress (due to torsion):**

$$\tau = \frac{T \cdot R}{J} \quad (2)$$

where $\boldsymbol{T}$ is the applied torque, $\boldsymbol{R}$ is the radial distance from the center (maximum at the outer surface), and $\boldsymbol{J}$ is the polar moment of inertia of the circular cross-section.

- **Normal Strain:**

$$\epsilon = \frac{\Delta L}{L_0} \quad (3)$$

where ΔL is the axial deformation and $L_0$is the original length of the specimen.

3. Results and Discussion

3.1 Tensile Loading

Figures 3 and 4 display the results of the finite element analysis. They show how tensile stress spreads through the AISI 1005 and AISI 1065 specimens. Both specimens were tested under the tensile loading conditions.
The tensile stress was calculated using Equation (1),The stress contours show an even distribution along the gauge section of each specimen. However, differences appear in the stress responses. These differences come from the material properties set for each steel grade. Under tensile loading AISI 1065 shows resistance to stress than AISI 1005. This matches AISI 1065's superior strength characteristics in the material model.

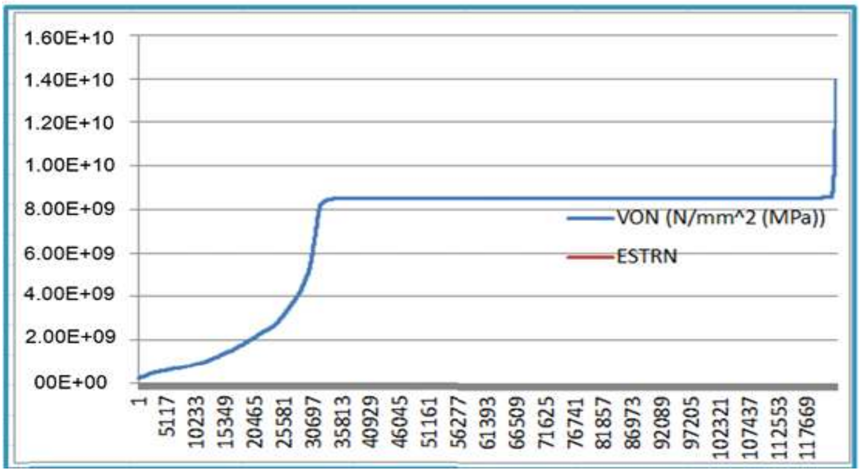

Figure 3: Tensile stress for AISI 1005.

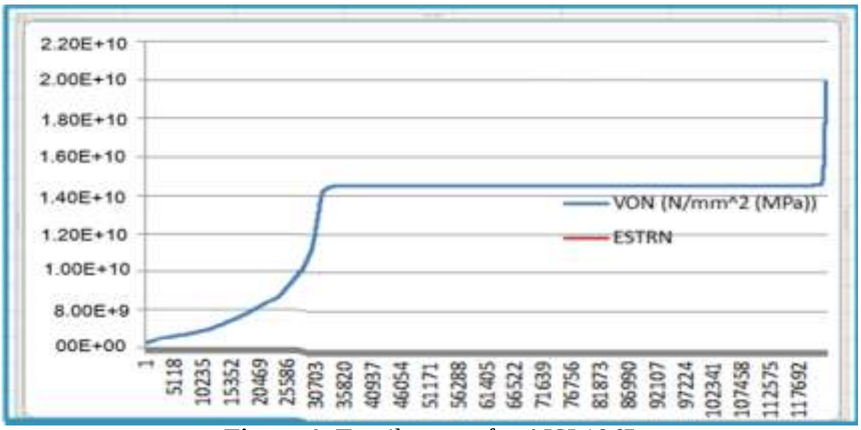

Figure 4: Tensile stress for AISI 1065

Figure 5 shows the tensile stress distribution in the AISI 1005–1065 specimen made by rotary friction welding. The numerical results show that tensile stress is effectively transferred across the interface of the two steels. There is a transition in the stress distribution between the AISI 1005 and AISI 1065 regions highlighting the differences in their mechanical properties. The numerical model does not show any localized stress concentration at the friction-welded interface suggesting that the joint maintains structural integrity and effective load transfer under tensile loading.

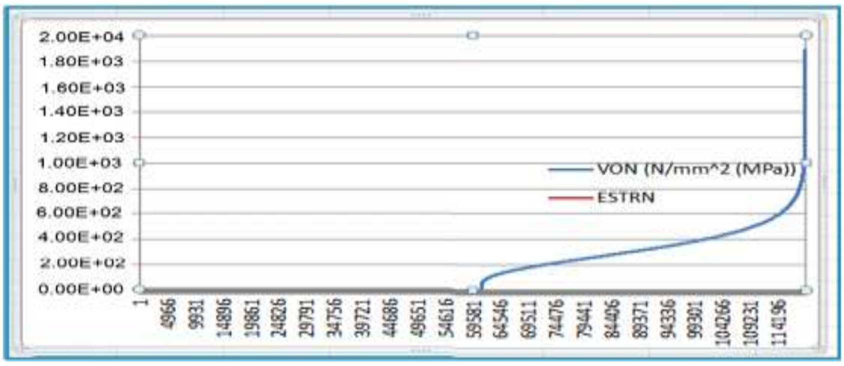

Figure 5: Tensile stress for the hybrid friction-welded specimen.

This smooth transfer of stress matches what has been observed in friction welding, a joining method. Friction welding reduces defects that often appear when metal melts and solidifies especially when compared to fusion welding techniques [16,8]. According to [17] The analysis shows that AISI 1065 has a stress-resistance response, then AISI 1005. The hybrid friction-welded setup also keeps stress moving across the joint under axial tensile loading. We cannot determine exact values of stress, strain or displacement because the original numerical output data is no longer available.

3.2 Torsional Loading

If you look at Figures 6–8 you can see how the shear stress spreads across the AISI 1005 the unwelded AISI 1065 and the friction-welded AISI 1005–1065 samples. We used Equation (2) to find the shear stress for every sample. In all these cases the shear stress follows a pattern that makes sense for a round shaft being twisted. The shear stress is at its highest on the edge. As you move toward the middle of the shaft the shear stress drops down until it is zero at the center.

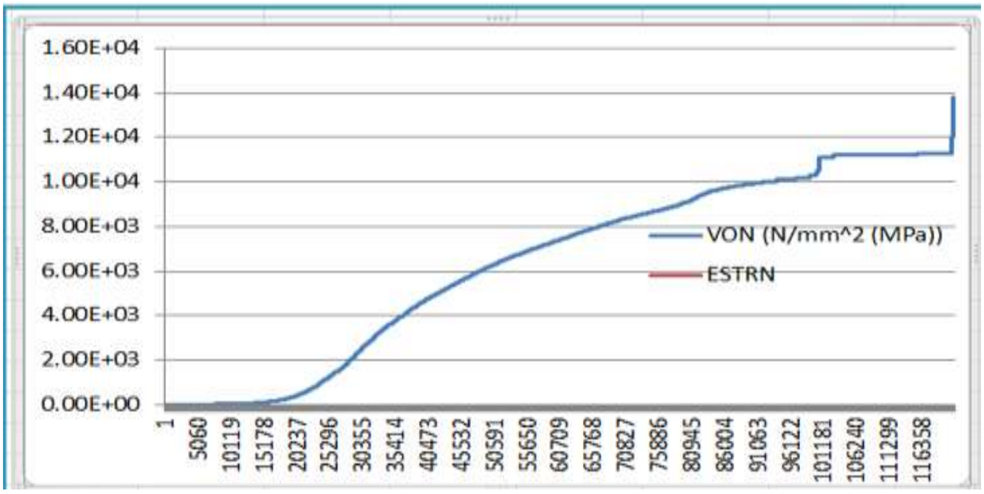

Figure 6: Torsional stress for AISI 1005.

When we apply the twisting force the AISI 1065 sample stays much stiffer than the AISI 1005 sample. I think this happens because AISI 1065 has carbon in it which makes AISI 1065 harder and stronger. Because of this the AISI 1065 will twist less than the AISI 1005 when you apply the same torque. On the hand the AISI 1005 is softer and more flexible so the AISI 1005 twists more easily. These results match what we saw during the tensile tests. Show how carbon content really changes how carbon steels behave.

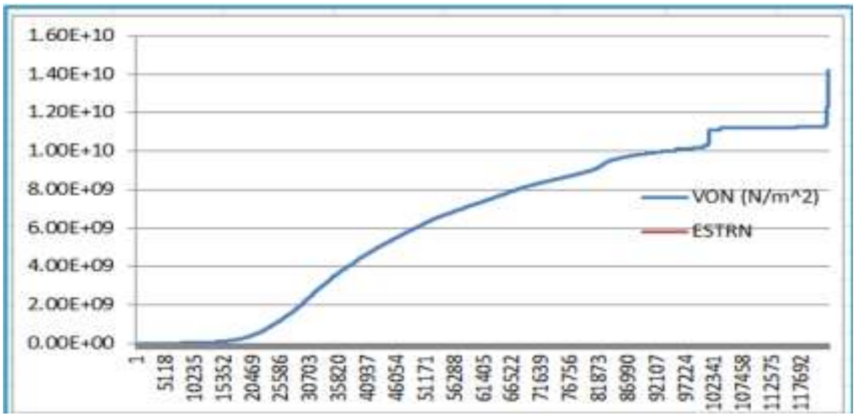

Figure 7: Torsional stress for AISI 1065.

Figure 8 shows the shear distribution for the hybrid AISI 1005–1065 sample that we made using friction welding. Our numbers show that the shear stress flows smoothly across the weld. I did not see any spots where the stress gets too high. Since the shear stress does not jump or break at the weld it looks like the welded joint does a job of passing the twisting force from one steel type to the other.

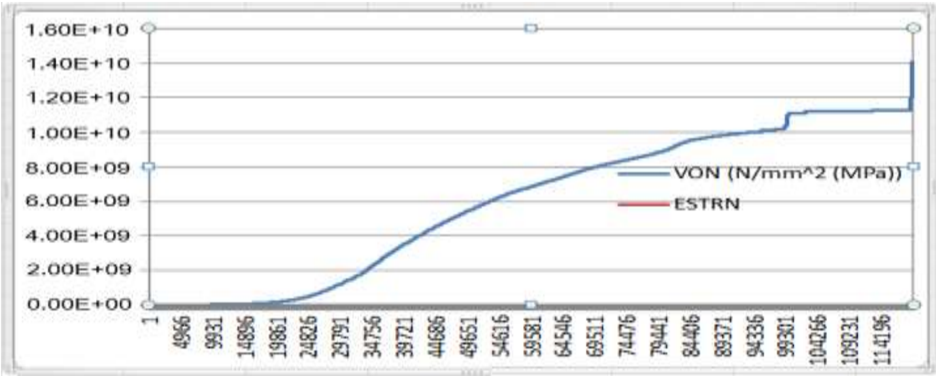

Figure 8: Torsional stress for the hybrid specimen.

The reason the shear stress moves well across the weld is because of how friction welding works as a solid-state joining method. My findings match what other researchers have found. They have also shown that friction welding can make strong joints between different steels so that the load moves well when the metal is under stress [17,16,8].

To sum up the tests show that AISI 1065 resists twisting than AISI 1005 under these specific loads. Also, the hybrid friction-welded sample shows a steady shear stress across the whole joint. I did not see any stress spikes in the model. This tells me that the friction-welded AISI 1005–1065 setup is a choice, for jobs that involve a lot of twisting.

3.3 Combined Tensile–Torsional Loading

Figures 9–11 show the stress distribution that comes from the finite element analysis for AISI 1005 AISI 1065 and the friction-welded AISI 1005–1065 hybrid specimen, all of them under a mix of tensile and torsional loading. The axial strain was determined using Equation (3). In contrast to the cases of only tensile or only torsional loading the combined loading creates a more intricate stress state because both normal stresses and shear stresses act at the same time on the specimens.

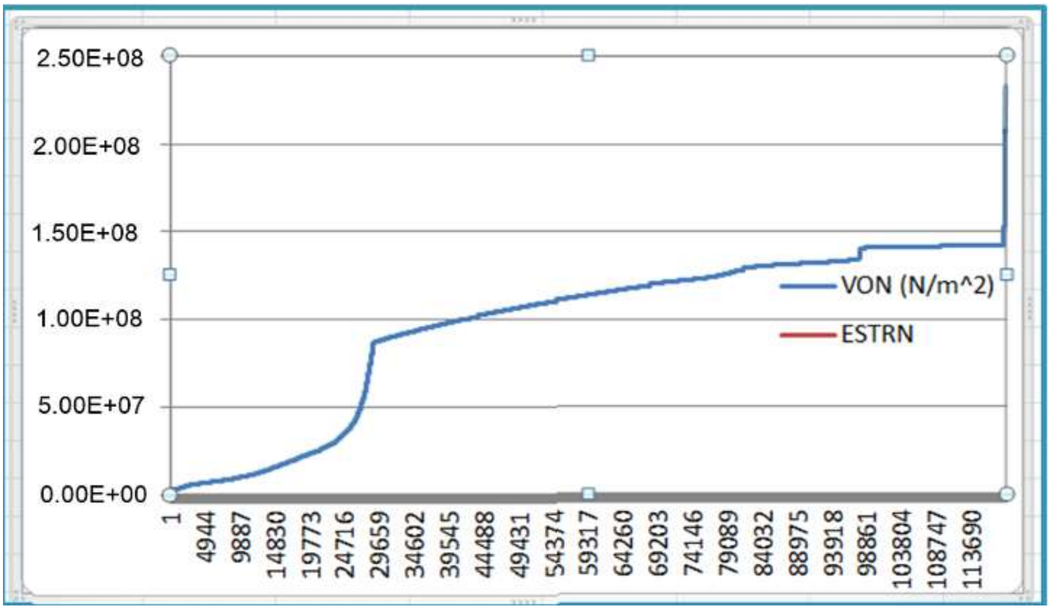

Figure 9: Combined loading for AISI 1005.

When it comes to specimens AISI 1065 shows a stronger resistance to combined loading conditions than AISI 1005. This can be attributed to AISI 1065's yield and tensile strength, which help it resist plastic deformation more effectively. On the side AISI 1005 with its lower strength and greater ductility tends to deform more easily under the same loading conditions. These findings highlight how the differences in carbon content and the resulting mechanical properties play a role in how these two steels respond to multiaxial loading.

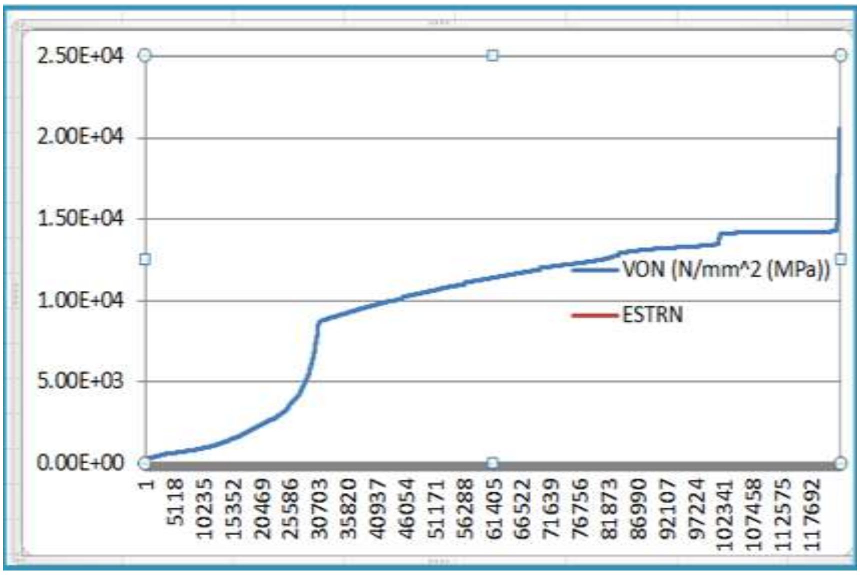

Figure 10: Combined loading for AISI 1065.

Figure 11 illustrates the stress distribution in the AISI 1005–1065 specimen created through friction welding. The numerical findings reveal that the stress state transitions, across the welded interface showing no significant stress concentration or mechanical discontinuity. The tensile stress gradually spreads through both the low-carbon and high-carbon steel areas and the torsional component is effectively managed across the joint. This behavior suggests that the welded interface is not a weak point when subjected to the applied combined loading conditions.

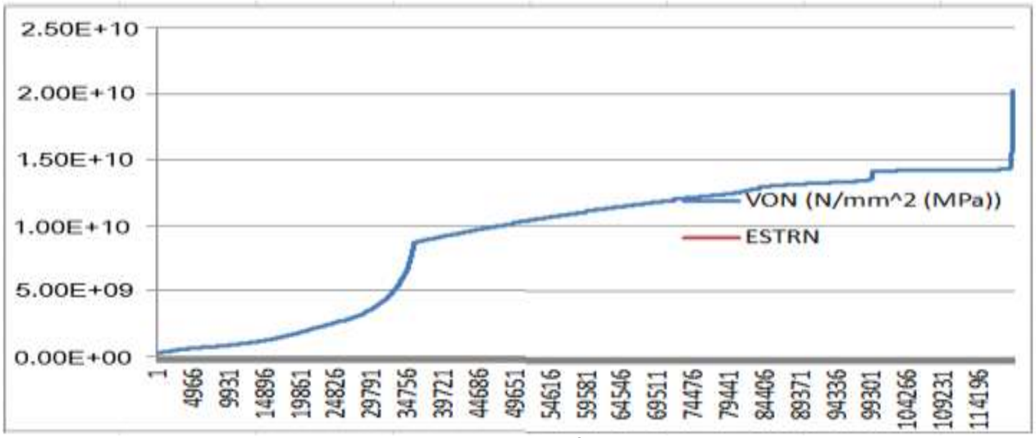

Figure 11: Combined loading for the hybrid specimen.

The constant stress movement that is visible in the sample shows that the friction-welded joint can deal with both pushing and twisting forces at the same time. This result is important because when both types of forces are applied together the material has difficulty than when just one force is used. The computer results support the idea that friction welding works for connecting AISI 1005 and AISI 1065 especially when the joint might experience tough stress situations. In short, the study of combined forces shows that AISI 1065 is better at resisting shape changes, than AISI 1005 while the hybrid friction-welded sample keeps the stress moving across the joined area. Also, the computer model shows that there is not a lot of stress building up at the joint which means the strength of the structure is good when both pulling and twisting forces are applied.

3.4 Comparative Analysis

The AISI 1065 steel specimen showed the mechanical resistance when put under the specified loading conditions. Thanks to its carbon content it boasts greater strength and hardness compared to the AISI 1005 specimen. As a result, it experienced strain when subjected to the axial and torsional loads. On the side the AISI 1005 specimen, with its lower carbon content offers higher toughness making it more ductile and easier to deform under stress. When it comes to the friction welded specimen its mechanical response falls somewhere between the two specimens. However, the simulation results indicated that there were no discontinuities or stress concentrations at the welding interface. This leads us to conclude that friction welding is a method for joining carbon steel parts. The joint formed is robust enough to handle both axial loads and it shows good mechanical compatibility with the hybrid structure. The finite element analysis further validated that friction welding is a technique for bonding carbon steel parts. The welds demonstrate reliability and resistance to deformation under complex loading scenarios. Thus, the analysis confirmed that friction welding can effectively create steel structures with impressive mechanical properties.

The research based on Finite Element Analysis (FEA) showcased in this paper highlights that beyond the properties of the individual materials the way the metals adhere to each other plays a crucial role in their overall performance. Through an analysis it was found that the specimen made from AISI 1065 steel delivered the best results in terms of tensile, torsional and combined mechanical performance thanks to its superior hardness and strength. On the hand the AISI 1005 steel specimen demonstrated better plasticity and deformability which can be attributed to its lower carbon content.

The findings are consistent with the trends regarding how carbon content affects the characteristics of carbon steel: as the carbon content rises, hardness and strength improve but plasticity takes a hit. The FEA results also indicate that the friction welding method successfully creates a joint between two specimens. As a result, the hybrid friction welded specimen can handle the applied torsional and tensile loads without showing any damage. The stress distribution analysis reveals that there are no stress points at the weld perimeter suggesting that friction welding is a reliable way to bond two different types of carbon steels. This study has demonstrated that using the friction welding technique to create a component with desirable properties is indeed feasible. A designed friction welded joint between two dissimilar carbon steels can provide the necessary mechanical benefits and reliability. Specifically, this hybrid component will leverage the strengths of both carbon and high-carbon steels making it ideal, for various applications that demand robust and resilient structural elements.

4. Conclusions

1. We looked at how non-welded AISI 1005 and AISI 1065 carbon steels act when we pull, twist or do both at the time. We used finite element analysis to see how the metals and their hybrid friction-welded joints handle these forces. Here is what we found: 1. In a pull test the non-welded AISI 1065 was stronger than the -welded AISI 1005. This is likely because the AISI 1065 has carbon, which makes the AISI 1065 harder. However, the non-welded AISI 1005 was not as strong. Was much more flexible.
2. The hybrid friction-welded AISI 1005–AISI 1065 specimen worked well under tensile loading. We did not see any stress jumps that would mean the hybrid friction-welded joint might break early.
3. When we twisted the metals the AISI 1065 was the best at resisting the twist. On the hand the AISI 1005 moved the most because the AISI 1005 is softer and stretchier.
4. Under twisting forces the hybrid friction-welded specimen showed an even spread of shear stress across the weld. We did not see any spots where the stress piled up. This tells us that the load moves smoothly across the friction-welded joint.
5. Out of all the tests we ran the combined tensile-torsional loading was the hardest on the materials. This shows that we really need to test friction-welded joints under these mixed conditions.
6. To sum it up our study shows that friction welding is a way to join AISI 1005 and AISI 1065. The metals hold up under tensile, torsional and mixed loads. Using SolidWorks Simulation was a way for us to check how the stress moves through both the non-welded and friction-welded specimens.

These results give us an idea of how well friction-welded AISI 1005 and AISI 1065 joints work in real life. This data shows that these joints are a choice, for making engineering parts that need to move loads safely between different carbon steels.

Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no conflict of interest.

Funding: This study was not funded by any organization, institution, or agency. The research was carried out independently by the authors without any external financial support.

Ethical Approval: This article does not contain any studies with human participants or animals performed by any of the authors. This study involved only numerical/computational finite element simulations of steel specimens; therefore, ethical approval was not required.

Informed Consent: Not applicable, as this study did not involve human participants.

Author Contributions: Both authors (Ahmed Salem Elmaalul and Abdelsamad M.B. Alflah) contributed equally to this work, including the conception and design of the study, the finite element simulations, analysis and interpretation of the results, and the writing and revision of the manuscript.

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