Proceedings of the 6th International Conference on Future of Education, Vol. 6, 2023, pp. 99-110

ISSN 2630-7413 online
DOI: https://doi.org/10.17501/26307413.2023.6108

ENHANCING GEOMETRICAL DIMENSIONING AND TOLERANCING PROFICIENCY: A PRACTICAL APPROACH TO TRAINING AND LEARNING

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Abstract: Geometrical Dimensioning and Tolerancing (GD&T) is a complex and detailed system used to communicate the design and manufacturing requirements of a part. GD&T is essential for the manufacturing industry as it ensures that parts are manufactured to the required specifications, reduces manufacturing errors and improves quality, simplifies communication between designers, manufacturers, and quality control personnel. Many technical schools and universities do not provide comprehensive training on GD&T, leaving students with limited exposure to the subject. This can make it challenging to acquire the necessary skills and knowledge to become proficient in GD&T. GD&T requires practical application to gain proficiency, and it can be challenging to find opportunities to practice in a real-world setting. Learning Geometrical Dimensioning and Tolerancing (GD&T) merely on a theoretical basis is not sufficient to become proficient in it. GD&T is a system that requires practical application to gain proficiency. This paper provides a review of teaching method used in a practical session designed for GD&T training and learning at a private technical institution. The finding from the review process will be used to conceptualise an effective pedagogy for GD&T training and learning.

Keywords - Geometrical Dimensioning and Tolerancing, Practical, Proficiency, Training and Learning

Introduction

Precision and accuracy are the foundations of successful products in the ever-changing world of engineering and production. Geometric Dimensioning and Tolerancing (GD&T) plays an important role in obtaining this precision by providing a standardised vocabulary for successfully communicating design specifications. As industries strive for increased efficiency and quality, workers must learn GD&T to enable efficient communication and error-free manufacturing processes. This study looks into the important subject of enhancing GD&T proficiency using a hands-on approach to teaching and learning.

The significance of GD&T proficiency cannot be understated, as it directly impacts product functionality, reliability, and overall cost-effectiveness. Miscommunication or misinterpretation of design requirements can lead to costly errors, delays in production, and even safety hazards. Traditional teaching approaches often rely heavily on theoretical concepts, which might leave learners struggling to apply GD&T principles practically. The main objectives of this study are to assess students' knowledge and understanding of GD&T concepts, evaluate the effectiveness of different training

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methodologies in educational institutions, and provide practical recommendations to enhance GD&T proficiency among students and practitioners. The study aims to contribute to the improvement of GD&T education and training, ensuring that students are well-equipped with the necessary knowledge and skills for successful application in real-world scenarios. Therefore, this study aims to shed light on the most effective methods of GD&T training and learning provided by training institutions.

Geometric dimensioning and tolerancing (GD&T) are crucial in engineering education for accurate communication of design specifications. Recent research focuses on innovative approaches to improve GD&T learning for undergraduate engineering students. (Paige, 2017) introduced spatial demonstration tools, enhancing visualization and comprehension of GD&T concepts through hands-on experiences. Their research showcased how spatial tools bridge the gap between theory and application, laying a strong foundation for engineering studies. (Yip-Hoi, 2017) explored model-based definition (MBD) integration to support GD&T learning in manufacturing engineering curricula. MBD provided virtual GD&T applications, aiding students in visualizing real-world manufacturing scenarios and enhancing their GD&T understanding. These studies contribute valuable insights to GD&T education, offering potential to revolutionize instruction, equip future engineers with practical skills, and promote effective communication in the engineering and manufacturing sectors. Further research in this area can advance GD&T education, leading to improved engineering practice and product quality.

(Waldorf, 2016) conducted a study at California Polytechnic State University, focusing on integrating GD&T into a manufacturing engineering curriculum. The goal was to develop competent GD&T practitioners capable of accurately interpreting and applying design specifications. The curriculum combined theoretical knowledge with hands-on training to provide practical experience in GD&T applications. Students engaged in real-world engineering projects, bridging the gap between theory and industry demands. The integration of GD&T throughout the curriculum emphasized the importance of precise communication in engineering and manufacturing. Practical training with modern measurement tools enhanced students' proficiency, preparing them for real-world scenarios and promoting critical thinking and problem-solving skills.

(Rios, 2018) conducted a study at the University of Texas, Dallas, focusing on enhancing GD&T teaching through 3-D computer models and 3-D printed parts. This innovative approach provided tangible and real-life examples of GD&T applications, transforming students' learning experience. Interacting with dynamic 3-D models, students visualized how GD&T symbols affect engineering designs in three-dimensional space. The use of 3-D printed parts allowed hands-on exploration, bridging theory and practical applications. This multi-modal approach accommodated different learning styles, improving students' comprehension of geometric tolerances' significance in design and manufacturing processes. (Ramlib, 2018) conducted a review highlighting GD&T's crucial role in the automotive industry, contributing to improved product quality, reduced errors, and increased manufacturing efficiency. (Lin *et al.* 2020) implemented a class infusion project at Old Dominion University, providing hands-on activities and access to modern measurement tools to enhance students' GD&T proficiency. Both studies underscore the significance of GD&T education in meeting industry demands and achieving standardization, preparing students for successful careers in manufacturing while addressing real-world challenges. (Blacklock, 2022) introduced an instructional scaffold approach to teaching GD&T at Western Colorado University Partnership Program, integrating industry feedback to ensure real-world relevance. Collaboration with industries exposed students to practical

GD&T applications, bridging theory and practice. This approach enhanced students' understanding and prepared them for engineering challenges in manufacturing. (Aidibe *et al.* 2020) conducted an interlaboratory study on GD&T measurement reproducibility, contributing to standardization and reliability in manufacturing processes. These studies collectively improve GD&T education and application, equipping students with practical skills and enhancing product quality and efficiency in industries.

(Hewerdine *et al.* 2011) explored integrating CAD and metrology tools to teach GD&T at the University of Illinois, Urbana-Champaign. This approach provided students practical experience in digital GD&T applications, using CAD software and metrology tools to create, analyse, and measure GD&T drawings. By combining theory with hands-on experience, students were better prepared for real-world engineering challenges and modern manufacturing practices. (Narang, 2018) emphasized teaching applied measuring methods using GD&T at Indiana University-Purdue University-Fort Wayne. Hands-on training with precision measuring instruments improved students' ability to interpret design specifications accurately and ensure product quality. Both studies highlight the importance of hands-on training and modern tools in GD&T education, preparing students for real-world engineering scenarios that demand GD&T proficiency and precise measurements for successful manufacturing processes and product quality assurance. (George, 2013) conducted a case study on the application of GD&T in the manufacturing process of a Dual Plate Check Valve. They demonstrated how using GD&T principles improved efficiency, reduced errors, and ensured product quality. By defining form, size, and orientation with GD&T specifications, the manufacturing process became streamlined, allowing for easier assembly and meeting required tolerances.

(Rios, 2019) provided a practical example of teaching GD&T using 3D printed parts. This hands-on approach allowed students to interact with tangible components, fostering a deeper understanding of GD&T concepts and their real-world applications. Both studies enhance GD&T education and prepare students for real-world engineering challenges, contributing to improved product quality and efficiency in manufacturing. (Talebi *et al.* 2020) explores the application of Geometric Dimensioning and Tolerancing (GD&T) principles in the construction industry. The study delves into how GD&T can be effectively integrated into construction projects, aiming to improve accuracy and communication in design specifications. By providing the DOI (Digital Object Identifier) number, the article is easily accessible for further reference and research. This work contributes valuable insights into the implementation of GD&T in the construction sector, potentially leading to enhanced product quality and reduced errors in construction processes.

(Cruz *et al.* 2019) conducted a systematic review to evaluate competency methods in engineering education. Their research in the European Journal of Engineering Education provided a comprehensive analysis of different approaches used to enhance students' competencies in engineering. The study offers insights into the strengths and weaknesses of each approach, aiding educators and policymakers in optimizing engineering education practices to meet industry demands. On the other hand, (Irawan *et al.* 2021) explored the integration of Geometrical Dimensioning and Tolerancing (GD&T) principles in product design skill development for TVET programs through a Computer Aided Design (CAD) module. Published in the Selangor Science & Technology Review's special issue on Science and Technology for Society, their research highlighted the importance of aesthetics in product design and the role of CAD and GD&T in fostering creativity and innovation in TVET curricula. By incorporating GD&T, the study emphasizes the significance of precise communication and interpretation of design

specifications, enhancing product quality and manufacturability. The findings provide valuable insights for educators and curriculum designers to develop effective TVET programs that nurture aesthetic values and practical product design skills, including the application of GD&T principles, thus preparing students for successful careers in the manufacturing industry.

Materials and Methods

The research methodology employed in this study follows a systematic approach to investigate GD&T education and training. The research objectives were defined as understanding the effectiveness and challenges of GD&T training. A qualitative research design was chosen to explore participants' perspectives and experiences. To ensure a representative sample, purposeful sampling was utilized, including both current students and workers who graduated from a Technical and Vocational Education and Training (TVET) institute. This approach allowed for a diverse range of participants with different levels of GD&T knowledge and experience.

Data collection was conducted through a survey questionnaire, which covered various aspects related to GD&T learning and training. The questionnaire included demographic information, GD&T knowledge and proficiency levels, perceptions of training effectiveness, and overall training experiences. This comprehensive survey aimed to gather detailed insights into learners' perspectives.

The survey responses were examined to identify common patterns and insights related to participants' experiences and perceptions of GD&T training. These findings were synthesized to draw meaningful conclusions and provide recommendations for enhancing GD&T proficiency. This will provide a deeper understanding of the effectiveness and challenges associated with GD&T training. Finally, the findings of the study will be disseminated through academic presentations and publications. The aim is to share the study outcomes with educators and industry professionals to foster discussions and promote improvements in GD&T education and training. The methodology used in this study is illustrated in Figure 1, which provides a comprehensive framework for the research process.

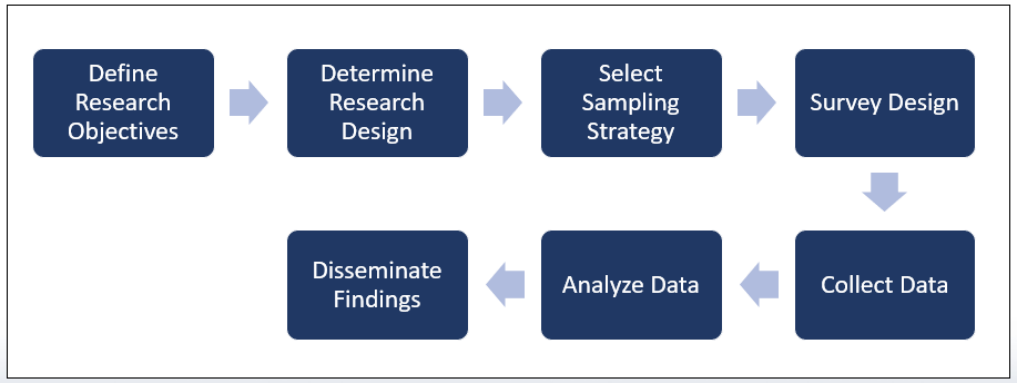

Figure 1: Framework of the Study Methodology

This study methodology was designed to effectively address the research objectives, providing valuable insights into the knowledge, experiences, and effectiveness of GD&T training. The dissemination of findings aimed to contribute to the improvement of GD&T education and training practices, ultimately enhancing participants' proficiency in GD&T concepts.

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Results and Discussion

The Results and Discussions section presents the findings and analysis of the study, focusing on GD&T education and training. It examines the demographic characteristics of the participants, explores the types of GD&T training received, evaluates participants' knowledge and understanding of GD&T concepts, and captures their training experiences and perceptions. The section aims to identify areas for improvement in GD&T training methodologies, highlight strengths and weaknesses, and provide practical recommendations to enhance GD&T proficiency.

Demographics

The findings regarding the demographics of the participants reveal important insights into the sample composition. The demographic data of the study participants reveals that the majority of respondents (70.8 %) are between the ages of 18 and 25. The gender distribution shows that 70.7% are male, while 29.3% are female. Among the participants, 61% are technical students and 39% are workers. Notably, a significant proportion (92.7%) have received formal training in GD&T. In terms of industry involvement, 39% of respondents reported being engaged in industries that require GD&T application, while 61% have no direct involvement. The results indicate that participants received different types of GD&T training. The majority (61.0%) had theoretical-only training focused on knowledge and understanding of GD&T concepts. A significant portion (31.7%) had practical-only training, emphasizing hands-on experience. A small percentage (7.3%) did not receive any GD&T training. These demographics provide valuable insights into the characteristics of the sample, encompassing age range, gender distribution, status, formal training, and industry involvement. Table 1 provides an overview of the demographic characteristics of the participants.

Table 1: Demographic Characteristics of Participants in the Study

Demographics	**Percentage**
Age	
18-25 years	70.8%
Above 26 years	29.2%
Gender	
Male	70.7%
Female	29.3%
Status	

Technical Students	61%
Industry Workers	39%
GD&T Training Received	
- Theoretical-only training	61.0%
- Practical-only training	31.7%
- No GD&T training received	7.3%
Industry Involvement	
Involved	39%
Not Involved	61%

Knowledge and Proficiency

The results indicate that 94.7% of participants self-assessed their GD&T knowledge and skills as medium to low, while only 5.3% considered themselves to have high proficiency. When it comes to familiarity with GD&T, only 13.2% of participants reported being very familiar with the concepts. Satisfaction with the GD&T training program varied, with 36.8% being highly satisfied, 26.3% moderately satisfied, and 36.8% neutral. In terms of confidence levels, 9.8% of participants were very confident in their GD&T proficiency, 80.5% had moderate confidence, and 9.8% lacked confidence. These percentages highlight the overall distribution of participants' self-assessment, familiarity, satisfaction, and confidence levels, shedding light on the current state of their knowledge and proficiency in GD&T. The distribution of participants' self-assessed knowledge and proficiency in GD&T is illustrated in Figure 2.

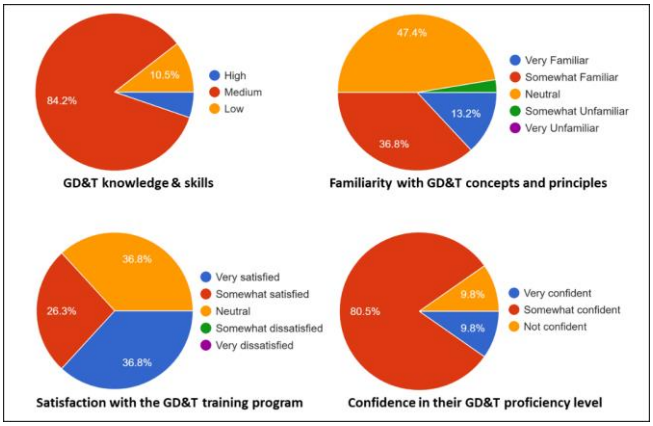

Figure 2: Participants' Self-Assessed Knowledge and Proficiency in GD&T

Training Effectiveness

The results reveal that 31.6% of the participants rated the training approach in GD&T as highly effective, while 68.4% found it to be moderately effective. This indicates a generally positive perception of the training's impact on participants' proficiency in GD&T. When examining the effectiveness of different training approaches, the combination of theoretical and practical training received the highest rating, with 73.7% of respondents considering it the most effective approach. The theoretical-only approach was rated as the most effective by 13.2% of participants, while the practical-only approach received a rating of 8.3%. These findings highlight the importance of incorporating practical components alongside theoretical instruction in GD&T training to maximize its effectiveness.

Furthermore, the results indicate that practical training activities had a significant impact on participants' understanding and application of GD&T principles. Nearly half of the respondents (48.8%) regarded practical training activities as extremely helpful, while 31.7% found them somewhat helpful.

This underscores the value of hands-on exercises and real-world applications in enhancing participants' grasp of GD&T concepts and their ability to apply them in practical scenarios. The chart in Figure 3 presents the effectiveness of various training approaches, as well as the perceived impact of practical training activities on understanding and applying GD&T principles.

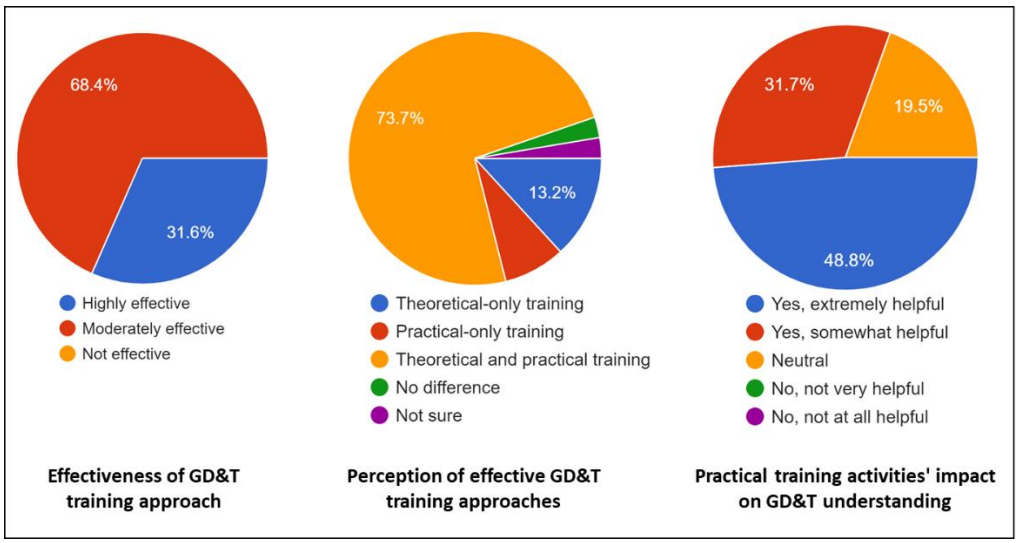

Figure 3: Effectiveness of GD&T Training Approaches and Impact of Practical Training Activities

The results of the study reveal that a significant percentage of respondents (78%) encountered difficulties during theoretical-only GD&T training. This indicates the challenges associated with this training approach. The difficulties reported can be attributed to several factors. Firstly, 53.7% of respondents found the complex nature of GD&T concepts to be a major hurdle. Interpreting engineering drawings was also identified as a challenge by 41.5% of participants. Additionally, 36.6% of respondents highlighted the lack of practical hands-on training, while 31.7% expressed the need for more examples and real-world applications.

When examining specific GD&T concepts and topics, the study found that modifiers such as MMC, LMC, and RFS were particularly difficult for 70.7% of respondents to understand. Other challenging areas included Datums and Datum Reference Frames (51.2%), Tolerance Zones (34.1%), Runout Tolerance (34.1%), Location Tolerance (29.3%), and various forms of Form Tolerance, Profile Tolerance, and Orientation Tolerance (24.4% each). It is worth noting that a small percentage of respondents (2.4%) found the concept of WCB (Regardless of Feature Size) challenging during their theoretical GD&T training. Figure 4 illustrates the challenging GD&T concepts and topics encountered during theoretical training.

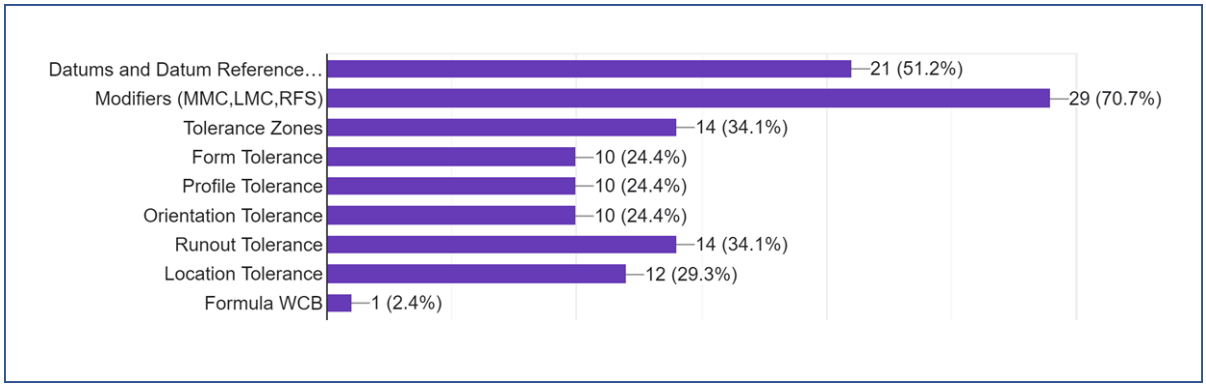

Figure 4: Challenging GD&T Concepts and Topics during Theoretical Training

These findings highlight the limitations of theoretical-only GD&T training and emphasize the need for a more comprehensive approach that incorporates practical components and addresses the specific challenges faced by participants. By bridging the gap between theory and practice, training programs can enhance understanding and proficiency in GD&T concepts.

The participants of the survey expressed their perspectives on the effective aspects of the practical training approach for GD&T. The findings revealed that certain elements were highly valued by the participants. These included hands-on practice with measurement tools, which allowed them to gain practical experience in applying GD&T principles. Real-life application examples were also considered important as they provided relevant and contextualized learning opportunities. In-depth training on GD&T fundamentals was identified as a key factor in building a strong foundation of knowledge. The use of simulations or software tools for GD&T practice was recognized as beneficial for enhancing practical skills. Interactive workshops and group discussions were valued for promoting active

engagement and collaborative learning among participants. Integrating theoretical concepts into practical scenarios was seen as a way to bridge the gap between theory and application effectively. Feedback and guidance from instructors during practical exercises were deemed essential for individual growth and improvement. Lastly, exposure to industry best practices was acknowledged as valuable, as it provided insights into real-world GD&T applications.

These findings highlight the importance of incorporating these effective aspects into GD&T training programs to enhance the overall learning experience and proficiency of participants. Figure 5 depicting the effective aspects of the practical GD&T training approach.

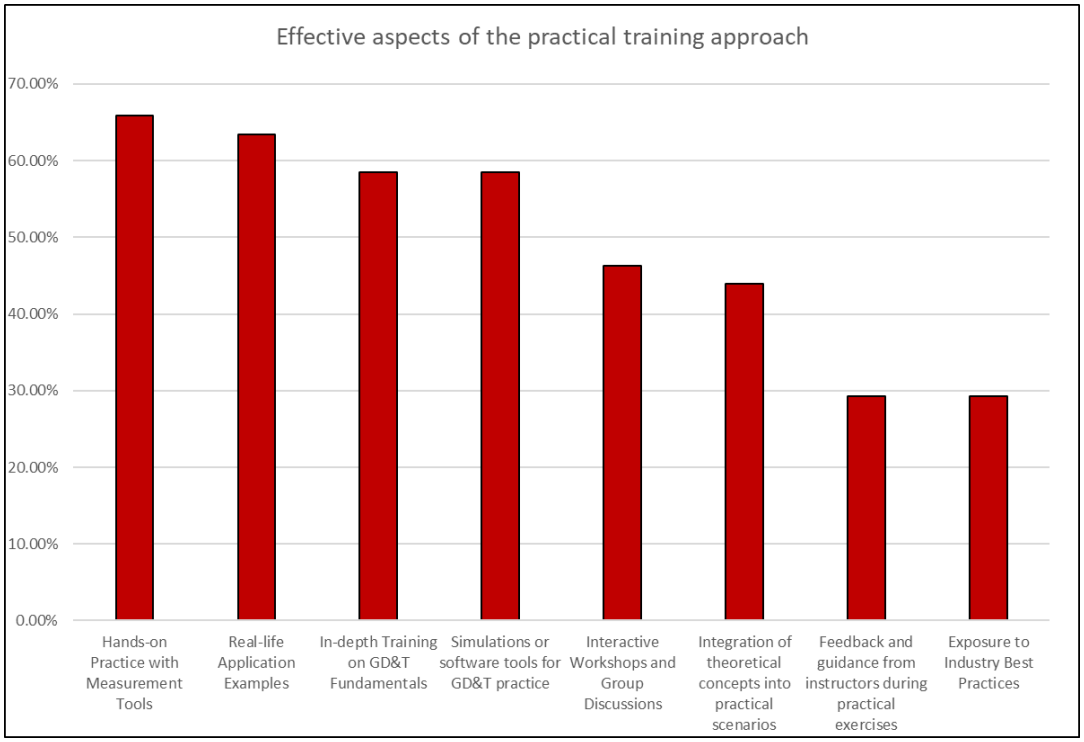

Figure 5: Effective Aspects of Practical GD&T Training Approach

Training Experience

The study also found that participants regarded the GD&T practical training approach, along with the provided practical kit, as effective in their GD&T training. Hands-on training and the use of practical tools positively contributed to their learning and skill development. Participants preferred diverse assessment methods, such as exercises with immediate feedback and case studies, to evaluate their practical skills and theoretical understanding. These findings emphasize the importance of incorporating practical elements and varied assessments to enhance participants' proficiency in GD&T. Figure 6 illustrates examples of the practical training exercises conducted using the provided practical kit to enhance their understanding and application of GD&T principles.

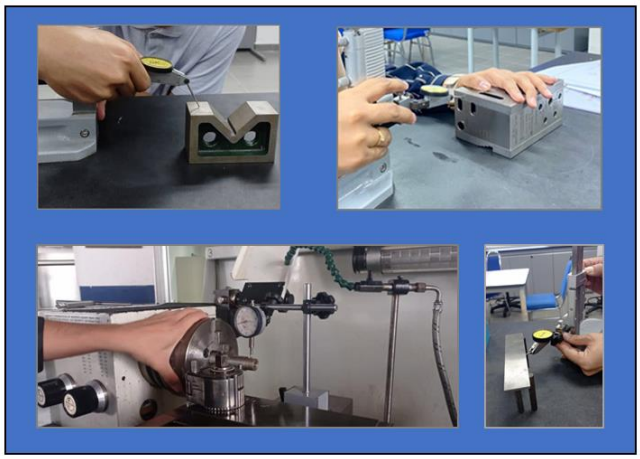

Figure 6: Examples of Practical Training Exercises Using the GD&T Practical Kit

The training experience of the participants highlighted the significant role of practical sessions and demonstrations in GD&T training. The vast majority of participants (95%) recognized the essentiality of practical components in their training. Practical sessions, demonstrations, and assessments were identified as key elements for effective GD&T training. Participants expressed a preference for half-day sessions conducted once a week, allowing sufficient time for hands-on practice and engagement. Additionally, they emphasized the importance of having demonstrations before each practical session, with an ideal duration of 1-2 hours, to ensure a clear understanding of the GD&T concepts. This feedback reinforces the value of well-structured and regular practical sessions and demonstrations in enhancing participants' understanding of GD&T principles and developing their practical skills effectively.

Conclusion

Based on the study findings, several recommendations can be derived to enhance GD&T proficiency among students. These recommendations include:

i. Design a well-structured curriculum that covers GD&T concepts from fundamental to advanced levels. This progressive education approach allows students to build a strong foundation and expand their knowledge gradually.

ii. Integrate theoretical concepts with practical applications. By providing real-world scenarios where students can apply GD&T principles, their understanding and skill development are reinforced.

iii. Employ interactive teaching methods, such as discussions, group activities, and hands-on exercises, to actively engage students and deepen their comprehension of GD&T.

iv. Implement a diverse range of assessment methods, including written tests, practical demonstrations, and project evaluations, to holistically evaluate students' GD&T proficiency.

In conclusion, the study emphasizes the importance of a comprehensive and practical-oriented approach to GD&T training. The findings highlight the need for a well-structured curriculum, integration of

theoretical and practical components, interactive teaching methods, and diverse assessment strategies. By adopting this pedagogical approach, educators and institutions can enhance GD&T proficiency among students, preparing them for successful careers in industries that require GD&T knowledge and skills.

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